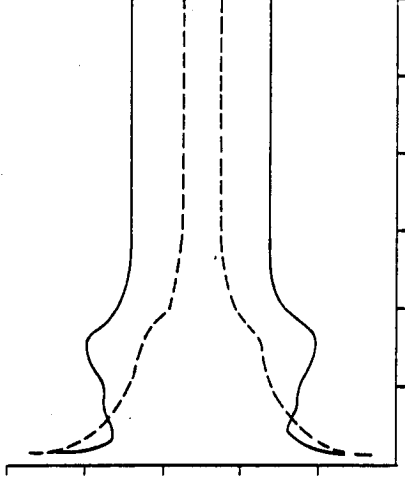


**OPTIMIZATION TECHNIQUES  
APPLIED TO  
PASSIVE MEASURES FOR IN-ORBIT  
SPACECRAFT SURVIVABILITY**

**HV410-12**

**FINAL REPORT  
(NAS8-37378)**



**Robert A. Mog  
D. Marvin Price**

**November 1987**

**Prepared for George C. Marshall Space Flight Center,  
Marshall Space Flight Center, AL 35812**

**BM21-8/21**

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"OPTIMIZATION TECHNIQUES APPLIED TO PASSIVE MEASURES FOR IN-ORBIT SPACECRAFT SUVIVABILITY" IS A SIX-MONTH STUDY, DESIGNED TO EVALUATE THE EFFECTIVENESS OF THE GEOMETRIC PROGRAMMING OPTIMIZATION TECHNIQUE IN DETERMINING THE OPTIMAL DESIGN OF A METEOROID AND SPACE DEBRIS PROTECTION SYSTEM FOR THE SPACE STATION CORE MODULE CONFIGURATION. THE EFFORT IS DIRECTED BY SHERMAN L. AVANS, ED52.

THE AUTHORS WISH TO THANK MR. AVANS FOR HIS OVERALL DIRECTION AND "REAL WORLD" INPUTS ON THIS STUDY. WE ALSO WANT TO THANK MS. JENNIFER HORN FOR PROVIDING DIRECTION ON THE DESIGN TRADES THAT WERE PERFORMED AS WELL AS MANY OF THE REFERENCES AND BASELINE PARAMETERS.

THE AUTHORS ALSO WISH TO THANK FRANCES CHEEK OF SAIC FOR HER CONSULTATIONS AND QUALITY REVIEW OF THIS REPORT.

BM27-8/21

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## **MOTIVATION**

- MANY FUNCTIONAL IMPACT PREDICTORS/MODELS ARE AVAILABLE
- MODELS ARE SOMETIMES CONFLICTING/CONFUSING
- MODELS ARE OFTEN NOT WELL-DOCUMENTED
- MODELS HAVE DIFFERENT PARAMETER SPACES AND DIFFERENT ORIGINS/ASSUMPTIONS
- FUNCTIONAL PREDICTORS ARE SUPERIOR TO NON-ANALYTICAL MODELS FOR DESIGNER TRADE-OFF STUDIES

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## **HOW THIS STUDY COMPLEMENTS OTHER EFFORTS**

- PROVIDES A TOOL FOR DISSECTING THE MASS OF IMPACT PREDICTORS/ MODELS AVAILABLE TO THE DESIGNER
- ESTABLISHES OPTIMAL DESIGN DATA BASED ON THE CURRENT PRE-DICTORS FOR COMPARISON WITH TESTING
- COMPLEMENTS BOEING'S EFFORTS WITH A HOST OF PERTINENT DESIGN TRADEOFFS
- ESTABLISHES A DATA BASE OF PREDICTOR ATTRIBUTES

BM09-9/9

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## WHAT YOU WILL SEE

- A DISCUSSION OF OPTIMIZATION TECHNIQUES
- SIGNIFICANT DESIGN TRADES FOR SEVERAL PREDICTORS UNDER DIFFERENT ASSUMPTIONS
- AN ASSESSMENT OF GEOMETRIC PROGRAMMING

## WHAT YOU WON'T SEE

- THE DEVELOPMENT OF NEW PREDICTORS
- THE NOMINATION OF A PREDICTOR
- A RECOMMENDED CORE MODULE DESIGN
- CONSIDERATION OF MLI, SUPPORT STRUCTURE, OR OTHER DESIGN ACCOUNTS (STRESS, THERMAL, ETC.)

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  - B. COMPUTER CODES

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## TERMINOLOGY

<u>WALL</u>	-	THE CORE MODULE PRESSURE SURFACE OR STRUCTURE
<u>BUMPER</u>	-	A SHIELD OR PLATE SPACED OUTBOARD FROM THE WALL
<u>OPTIMAL RATIO</u>	-	THE THICKNESS DISTRIBUTION (IN PERCENT) BETWEEN THE BUMPER AND WALL THAT OPTIMIZES THE DESIGN OBJECTIVE
<u>"WEIGHT"</u>	-	THE SUM OF THE BUMPER AND WALL THICKNESSES
<u>WEIGHT</u>	-	THE THEORETICAL DRY CORE MODULE EARTH-MASS AS ATTRIBUTED TO THE BUMPER AND WALL THICKNESSES AND MODULE CONFIGURATION.
<u>MISSION RISK</u>	-	ONE MINUS THE PROBABILITY OF NO PENETRATION
<u>INDEPENDENT VARIABLE(S)</u>	-	THE PARAMETER(S) THAT ARE CONTROLLABLE IN SOME SENSE BY THE SYSTEM DESIGNER
<u>GLOBAL</u>	-	A FORM OF OPTIMIZATION THAT RESULTS IN THE OVERALL OR COMPREHENSIVE BEST SOLUTION
<u>LOCAL</u>	-	A FORM OF OPTIMIZATION THAT RESULTS IN THE BEST SOLUTION FOR SOME NEIGHBORHOOD OF THE INDEPENDENT VARIABLE

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## TERMINOLOGY (CONTINUED)

- FUNCTIONAL - A MATHEMATICAL RELATIONSHIP THAT MAY BE WRITTEN EXPLICITLY
- PREDICTOR - A MODEL, EITHER FUNCTIONAL OR NON-ANALYTICAL, WHICH DESCRIBES THE IMPACT PHYSICS (E.G., NYSMITH, WILKINSON, BURCH, MODIFIED BURCH, PEN4, BOEING, MADDEN, RICHARDSON)
- NONLINEAR - A PREDICTOR WHOSE INDEPENDENT VARIABLES HAVE EXPONENTS THAT ARE NOT ALL EQUAL TO UNITY
- DEGREE-OF-DIFFICULTY - IN AN OPTIMIZATION TECHNIQUE, THE NUMBER OF VARIABLES THAT MUST BE SOLVED FOR MINUS THE NUMBER OF INDEPENDENT EQUATIONS AVAILABLE
- CONSTRAINT - AN EQUATION OR INEQUALITY WHICH LIMITS THE USAGE OF A PREDICTOR
- POSYNOMIAL - A POLYNOMIAL WITH POSITIVE COEFFICIENTS AND WHOSE INDEPENDENT VARIABLES ARE POSITIVE-VALUED

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## TERMINOLOGY (CONTINUED)

- PARAMETER SPACE - THE TOTAL NUMBER OF POSSIBLE INDEPENDENT VARIABLES ASSOCIATED WITH A PREDICTOR
- IDEALIZED SCENARIO - AN IMPACT SCENARIO SIMILAR TO A TEST SETUP AND CHARACTERIZED BY FLAT PLATES MODELLING THE BUMPER AND WALL AND NO SUPPORT STRUCTURE
- OBJECTIVE FUNCTION - THE EQUATION OR FUNCTION WHICH CHARACTERIZES THE OPTIMIZATION GOAL OF THE SYSTEM DESIGNER
- INFLECTION - A POINT IN A DESIGN TRADEOFF CURVE AT WHICH THE SLOPE CHANGES FROM DECREASING TO INCREASING, OR VICE VERSA
- PIECEWISE CONTINUOUS - A SET OF EQUATIONS, EACH OF WHICH IS CONTINUOUS, BUT WHEN COMBINED, MAY BE DISCONTINUOUS AT A FINITE NUMBER OF POINTS (E.G., WILKINSON, BOEING PREDICTORS)
- MONOTONIC - STRICTLY INCREASING, DECREASING, OR CONSTANT

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# **SECTION I**

## **OPTIMIZATION TECHNIQUES BACKGROUND AND COMPARISON**

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# WHAT YOU WILL SEE IN SECTION I

- PROTECTIVE SYSTEMS DESIGN OPTIMIZATION PROBLEM FORMULATION
- DISCUSSION OF SPECIFIC OPTIMIZATION TECHNIQUE ATTRIBUTES
- EXAMPLE APPLICATION

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## WHAT OPTIMIZATION MEANS IN THIS STUDY

FINDING THOSE DESIGN THICKNESSES WHICH PROVIDE THE GREATEST PROTECTIVE CAPABILITY (WITH RESPECT TO THE METEOROID AND SPACE DEBRIS ENVIRONS) WHILE INDUCING THE LEAST WEIGHT, AND THUS COST.

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## **WHY THIS DESIGN OPTIMIZATION IS IMPORTANT**

- METEOROID AND SPACE DEBRIS ENVIRONS  
OFTEN DRIVE STRUCTURAL DESIGN
- SAFETY IS A HIGH PRIORITY
- DESIGN FEASIBILITY IS AT STAKE
- THE ENVIRONMENT IS NOT STATIC
- POLICY IS SIGNIFICANTLY AFFECTED BY COST
- IMPACT SCIENCE IS YOUNG

BM10-9/9

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## PARAMETERS AND THE TASK OF THE SYSTEM DESIGNER

THE BASIC PARAMETERS ASSOCIATED WITH DESIGN OF THE PROTECTIVE SYSTEMS FOR SPACECRAFT WHICH MUST ENDURE THE THREAT OF METEOR- OIDS AND SPACE DEBRIS MAY BE CATEGORIZED AS MISSION PARAMETERS AND DESIGN PARAMETERS. TYPICALLY, MISSION PARAMETERS SUCH AS ORBIT, ACCEPTABLE MISSION RISK, MISSION DURATION, AND SPACECRAFT SIZE ARE USED TO DETERMINE THE DESIGN PROJECTILE MASS AND DIAMETER. THE PROJECTILE VELOCITY IS THEN CONSIDERED TO COMPLETE THE SET OF THREAT CHARACTERISTICS. DESIGN PARAMETERS SUCH AS BUMPER/WALL THICKNESS, DENSITIES, AREAS, AND SEPARATION ARE USED TO ASSESS THE EFFECTIVENESS OF THE DESIGN IN RESISTING PROJECTILE PENETRATION.

THE SYSTEM DESIGNER'S ROLE IS TO CREATE OR CHOOSE A RELATIONSHIP BETWEEN THE REQUIRED DESIGN PARAMETERS AND THE MISSION AND THREAT PARAMETERS. THE DESIGNER MUST THEN OPTIMIZE AN OBJECTIVE FUNCTION COMPOSED OF THE DESIGN PARAMETERS, E.G., WEIGHT.

BM01-9/1

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# PARAMETERS AND THE TASK OF THE SYSTEM DESIGNER

- **PARAMETERS**
  - **MISSION (THREAT):** PROJECTILE CHARACTERISTICS — DETERMINED FROM ORBIT (DEFINES ENVIRONMENT), ACCEPTABLE LEVEL OF RISK FOR MISSION, MISSION DURATION, SPACECRAFT SIZE
  - **DESIGN:** CONFIGURATION-SPECIFIC PARAMETERS OF PROTECTIVE SYSTEMS (e.g., thicknesses, densities, dimensions)
- **THE SYSTEM DESIGNER'S ROLE**
  - DETERMINE THE DESIGN PARAMETERS BASED ON THE MISSION PARAMETERS
  - OPTIMIZE A SPECIFIC FUNCTION OF THESE DESIGN PARAMETERS

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## CLASSICAL APPROACHES

IMPACT PREDICTORS MAY BE CLASSIFIED AS FUNCTIONAL OR NON-ANALYTICAL. AMONG FUNCTIONAL PREDICTORS, ONE HAS THEORETICAL (E.G., MADDEN EQUATION) AND EXPERIMENTAL (E.G., NYSMITH EQUATION) MODELS. NON-ANALYTICAL MODELS SUCH AS THE HULL CODE TYPICALLY ARE NUMERICAL TECHNIQUES EMPLOYING PARTIAL DIFFERENTIAL EQUATIONS TO SOLVE THE EQUATIONS OF SOLID AND FLUID MECHANICS.

THE FIRST STEP IN THE OPTIMIZATION PROCESS IS TO DEVELOP THE OBJECTIVE FUNCTION(S) IN TERMS OF FUNCTIONAL PREDICTOR(S). TYPICAL FUNCTIONS DESCRIBE LAUNCH WEIGHT OR COST ASSOCIATED WITH PROTECTIVE SYSTEMS.

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## CLASSICAL APPROACHES

- **PREDICTORS RELATE MISSION TO DESIGN PARAMETERS**
  - FUNCTIONAL: THEORETICAL VS EXPERIMENTAL (e.g., Nysmith Equation)
  - NON-ANALYTICAL (e.g., HULL Code)
- **OPTIMIZATION FUNCTIONS COMPOSED OF FUNCTIONAL PREDICTORS**
  - FUNCTIONS DESCRIBING LAUNCH WEIGHT ASSOCIATED WITH PROTECTIVE SYSTEMS
  - FUNCTIONS DESCRIBING COST ESTIMATING RELATIONSHIPS ASSOCIATED WITH PROTECTIVE SYSTEMS

## IDEALIZED SPACECRAFT IMPACT SCENARIO

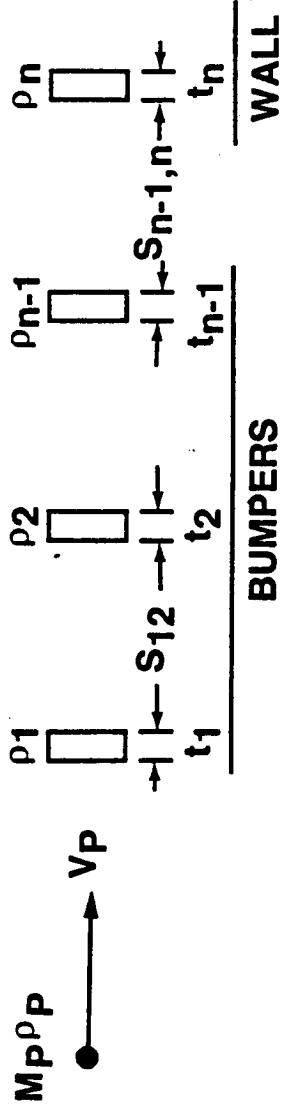
FOR ANALYSIS PURPOSES, AN IDEALIZED SCENARIO WAS DEVELOPED AS A BASIS TO COMPARE VARIOUS PREDICTORS.

THIS IDEALIZED SCENARIO IS SHOWN FOR A FAIRLY COMPLETE SET OF DESIGN AND PROJECTILE CHARACTERISTICS. THE "WEIGHT" FUNCTION ASSUMED IS THE PRODUCT OF THE PLATE DENSITY AND PLATE THICKNESS SUMMED OVER THE TOTAL NUMBER OF PLATES. AS WE SHALL SEE, FOR THE NYSMITH PREDICTOR, THERE IS ONLY ONE BUMPER AND ONE WALL. FURTHERMORE, THE NYSMITH PREDICTOR SHOWS NO DEPENDENCE ON BUMPER/WALL DENSITIES. THEREFORE, THE BUMPER THICKNESS IS THE INDEPENDENT VARIABLE, AND THE "WEIGHT" FUNCTION IS SUFFICIENTLY EXPRESSED AS THE SUM OF THE BUMPER AND WALL THICKNESSES.

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# IDEALIZED SPACECRAFT IMPACT SCENARIO



$M_p$	=	mass of projectile
$\rho_p$	=	density of projectile
$V_p$	=	velocity of projectile
$t_i$	=	bumper thickness, $i = 1, 2, \dots, n-1$ ,
$t_n$	=	wall thickness,
$\rho_i$	=	bumper density, $i = 1, 2, \dots, n-1$ ,
$\rho_n$	=	wall density
$S_{i,i+1}$	=	distance between bumper $i$ and bumper $i+1$ .

"WEIGHT" FUNCTION:

$$W_T = \sum_{i=1}^n \rho_i t_i \quad \text{for constant normal plate areas.}$$

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## ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES

THE TRADITIONAL APPROACH TO CONTINUOUS AND OFTEN NONLINEAR FUNCTIONAL OPTIMIZATION HAS BEEN TO APPLY EXTREMA THEOREMS FROM THE CALCULUS. HOWEVER, THIS APPROACH ONLY PROVIDES SUFFICIENT CONDITIONS FOR LOCAL EXTREMA. THUS, THIS TECHNIQUE MAY FAIL IN TWO ENTIRELY DIFFERENT WAYS. IT MAY FAIL TO LOCATE CERTAIN EXTREMA, AND IF IT DOES LOCATE AN EXTREMA POINT FOR THE PROBLEM, THERE IS NO GUARANTEE THAT IT IS A GLOBAL EXTREMA. FURTHERMORE, THIS METHOD REQUIRES THE EVALUATION OF PARTIAL DERIVATIVES AND HAS NO PROVISIONS FOR INEQUALITY CONSTRAINTS INCLUDED IN THE PROBLEM FORMULATION. FINALLY, THIS METHOD IS CUMBERSOME FOR PROTECTIVE SYSTEMS WITH A LARGE NUMBER OF BUMPERS, SINCE THE NUMBER OF DETERMINANTS AND THE ORDER OF THE HIGHEST ORDERED DETERMINANT IS PRECISELY EQUAL TO THE NUMBER OF BUMPERS.

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# ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES

## TRADITIONAL APPROACH

- THE EXTREMA THEOREM (ET) METHOD
  - APPLIES TO FUNCTIONAL PREDICTORS ONLY
  - PROVIDES SUFFICIENT CONDITIONS FOR LOCAL EXTREMA
  - NUMBER OF DETERMINANTS TO BE COMPUTED IS EQUAL TO THE NUMBER OF BUMPERS
  - ORDER OF HIGHEST ORDERED DETERMINANT IS EQUAL TO THE NUMBER OF BUMPERS
  - REQUIRES EVALUATION OF PARTIAL DERIVATIVES
  - HAS NO PROVISIONS FOR INEQUALITY CONSTRAINTS

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## ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES (CONTINUED)

CONTRARY TO THE TRADITIONAL EXTREMA THEOREM APPROACH, THE GEOMETRIC PROGRAMMING TECHNIQUE PROVIDES THE GLOBAL OPTIMIZATION OF THE PROBLEM, PROVIDED IT IS FORMULATED IN POSYNOMIAL FORM. A POSYNOMIAL IS A POLYNOMIAL WITH POSITIVE COEFFICIENTS AND POSITIVE VALUES OF THE INDEPENDENT VARIABLES. A QUICK REVIEW OF THE VARIABLES SHOWN UNDER THE IDEALIZED SPACECRAFT IMPACT SCENARIO SHOWS THAT THE VARIABLES ASSOCIATED WITH THIS PROBLEM ARE INHERENTLY POSITIVE-VALUED. THUS, THE ONLY REQUIREMENT FOR GLOBAL OPTIMIZATION OF THESE TYPES OF PROBLEMS IS THAT THE IMPACT PREDICTOR BE A POLYNOMIAL WITH POSITIVE COEFFICIENTS. ANOTHER ADVANTAGE TO GEOMETRIC PROGRAMMING IS THE METHOD'S ABILITY TO ACCOMMODATE MANY TYPES OF INEQUALITY CONSTRAINTS.

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# ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES

## (Continued)

### ALTERNATIVE APPROACH

- THE GEOMETRIC PROGRAMMING (GP) METHOD
  - EMPLOYS THE ARITHMETIC-GEOMETRIC INEQUALITY
  - APPLIES TO POSYNOMIALS (POSITIVE-VALUED POLYNOMIALS) ONLY
  - RESULTS IN GLOBAL OPTIMIZATION OF THE POSYNOMIAL
  - ACCOMMODATES MOST INEQUALITY CONSTRAINTS

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## APPLICATIONS OF OPTIMIZATION METHODOLOGY

THE NYSMITH EQUATION WITH VARIABLE DEFINITION IS SHOWN FOR REFERENCE. NOTE THAT THERE IS NO DEPENDENCE ON BUMPER, WALL, OR PROJECTILE DENSITIES. THUS, WE SAY THAT THE NYSMITH PREDICTOR FORMS AN INCOMPLETE SET OF PARAMETERS. THE NYSMITH PREDICTOR IS ANALYZED BY BOTH OPTIMIZATION TECHNIQUES FOR THE ZERO DEGREE-OF-DIFFICULTY CASE WITH CONSISTENT RESULTS. IT IS ANALYZED USING GEOMETRIC PROGRAMMING ONLY FOR THE TWO DEGREE-OF-DIFFICULTY CASE, SINCE THE EXTREMA THEOREM METHOD DOES NOT HANDLE INEQUALITY CONSTRAINTS.

BM06-9/1

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# APPLICATIONS OF OPTIMIZATION METHODOLOGY

- THE NYSMITH EQUATION

$$\frac{t_2}{d} = \frac{5.08 V^{.278}}{\left(\frac{t_1}{d}\right)^{.528} \left(\frac{h}{d}\right)^{1.39}}, \text{ valid for}$$

$$\frac{t_1}{d} \leq 0.5 \text{ and } \frac{t_2}{d} \leq 1.0 ,$$

where

- $V$  = projectile velocity,
- $d$  = projectile diameter,
- $t_1$  = bumper thickness,
- $t_2$  = wall thickness,
- $h$  = bumper wall separation

- INCOMPLETE SET OF PARAMETERS
- ANALYZED BY BOTH METHODS FOR ZERO DEGREE OF DIFFICULTY CASE (METHODOLOGY CONSISTENT) AND BY GP METHOD FOR 2 DEGREE OF DIFFICULTY CASE.

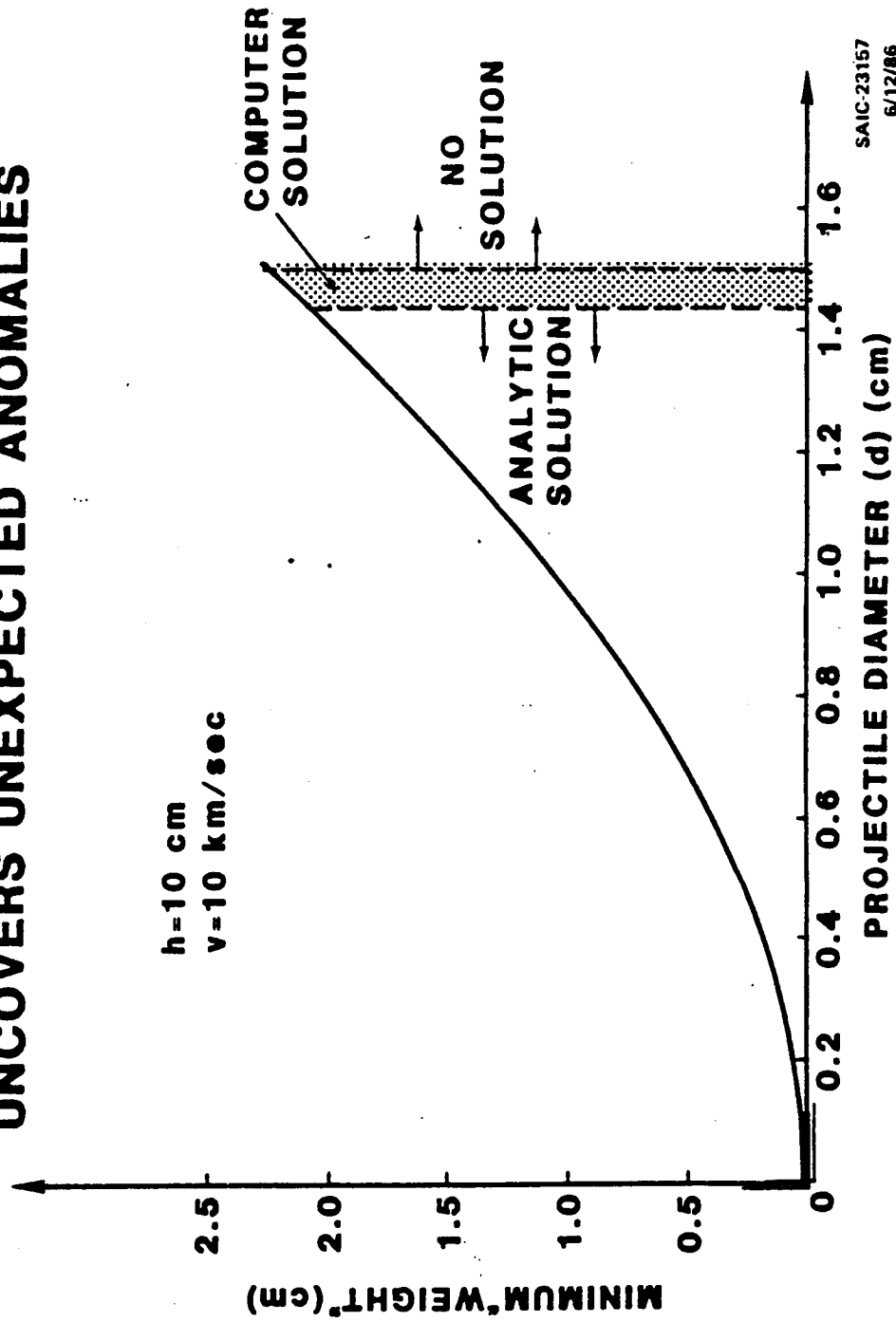
## **GP METHOD SEPARATES SOLUTION REGIONS AND UNCOVERS UNEXPECTED ANOMALIES**

THE DEPENDENCE OF OPTIMAL DESIGN ON PROJECTILE DIAMETER IS SHOWN FOR A HYPOTHETICAL SCENARIO. IT TURNS OUT THAT THERE ARE THREE SOLUTION REGIONS ASSOCIATED WITH THE NYSMITH PREDICTOR. IN THE ANALYTIC SOLUTION REGION, IT IS DISCOVERED THAT THE MINIMUM "WEIGHT" MAY BE WRITTEN ANALYTICALLY IN TERMS OF THE SOLUTION PARAMETERS. IN THE COMPUTER SOLUTION REGION, THE GEOMETRIC PROGRAMMING DUAL VARIABLES MUST BE ITERATED TO OBTAIN THE OPTIMAL SOLUTION. FINALLY, IT IS FOUND THAT THERE EXISTS A REGION OF NO SOLUTION WHICH CORRESPONDS WITH A THIRD, PREVIOUSLY UNDISCOVERED, INEQUALITY CONSTRAINT TO THE NYSMITH PREDICTOR. THIS INEQUALITY CONSTRAINT IS INDEPENDENT OF THE ORIGINAL TWO CONSTRAINTS AND RESTRICTS THE APPLICABILITY OF THE NYSMITH PREDICTOR.

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# GP METHOD SEPARATES SOLUTION REGIONS AND UNCOVERS UNEXPECTED ANOMALIES



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**AVERAGE CUMULATIVE TOTAL METEOROID  
FLUX-MASS MODEL FOR 1 A.U.**

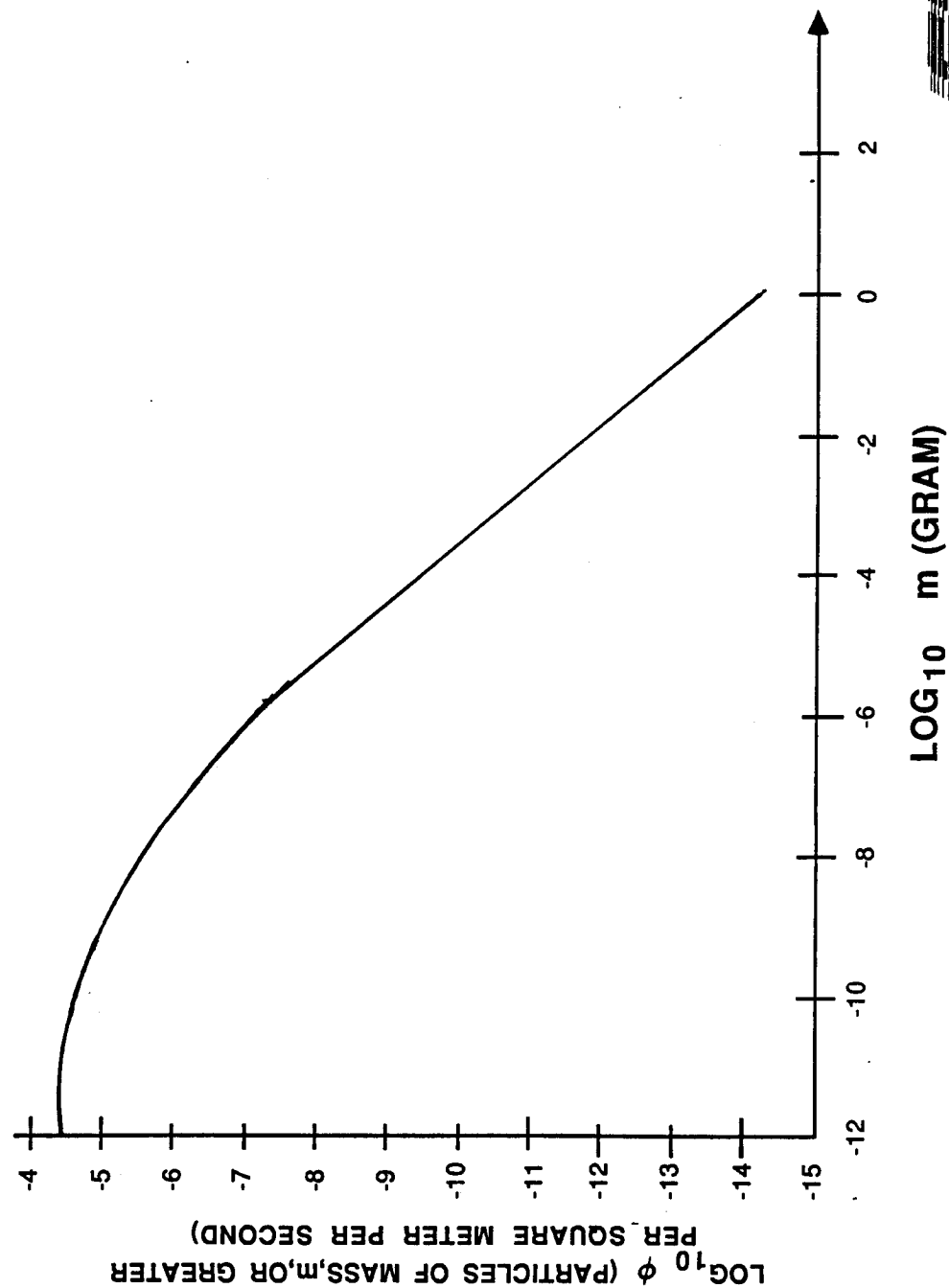
**THE RELATIONSHIP BETWEEN METEOROID FLUX AND MASS WAS EXTRACTED  
FROM NASA TM-86466, "A REVIEW OF MICROMETEOROID FLUX MEASURE-  
MENTS AND MODELS FOR LOW ORBITAL ALTITUDES OF THE SPACE STATION",  
BY MICHAEL SUSKO, SEPTEMBER, 1984.**

BM08-9/1

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AVERAGE CUMULATIVE TOTAL METEOROID FLUX-MASS  
MODEL FOR 1 A.U.



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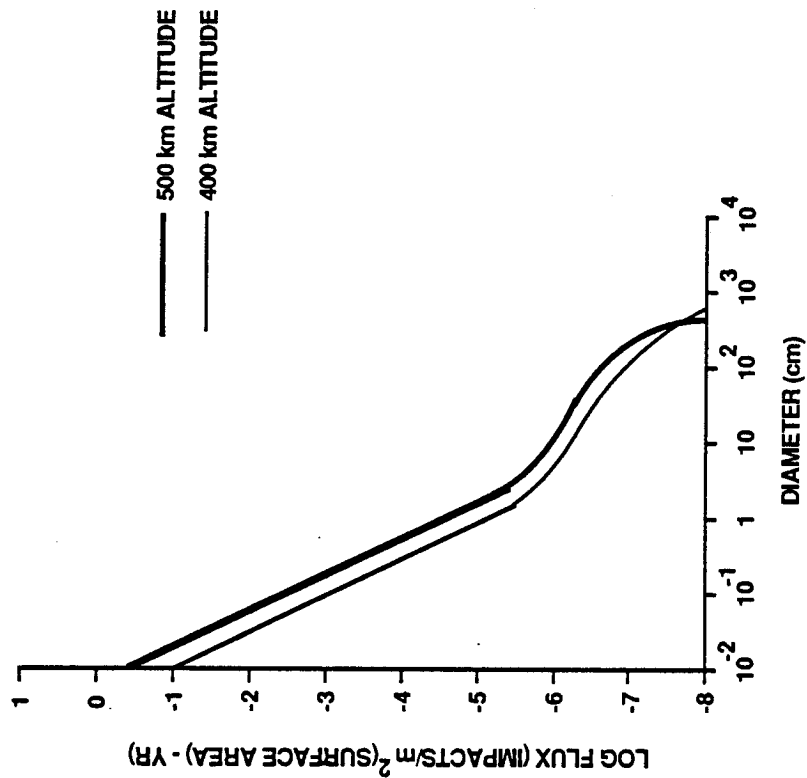
## 1990's AVERAGE ENVIRONMENT

THE AVERAGE ORBITAL DEBRIS ENVIRONMENT FOR THE 1990's IS SHOWN FOR 400 AND 500 Km ALTITUDES. THIS DATA WAS EXTRACTED FROM JSC-20001, "ORBITAL DEBRIS ENVIRONMENT FOR SPACE STATION", DONALD J. KESSLER. NOTE THE SHARP INFLECTION POINTS OCCURRING AT A DIAMETER OF 1 CM.

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# 1990's AVERAGE ENVIRONMENT



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## **SECTION II**

### **NYSMITH PREDICTOR APPLIED TO IDEALIZED SCENARIO**

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## WHAT YOU WILL SEE IN SECTION II

- A COMPARISON OF METEOROID AND DEBRIS ENVIRONS FOR THE NYSMITH PREDICTOR-IDEALIZED SCENARIO
- OPTIMAL THICKNESS DISTRIBUTIONS FOR THE NYSMITH PREDICTOR
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
  - BUMPER/WALL SEPARATION
  - PROJECTILE DIAMETER
  - PROJECTILE VELOCITY
  - MISSION RISK
  - MISSION DURATION

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## **BASELINE DESIGN PARAMETERS**

**THE MARCH 1987 BASELINE DESIGN PARAMETERS USED FOR ANALYSIS OF THE NYSMITH PREDICTOR ARE SHOWN. THESE PARAMETERS IMPLY A BASELINE OPTIMAL (NYSMITH) DESIGN THAT IS ROUGHLY 1.5 TIMES THE CURRENT DESIGN.**

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# BASELINE DESIGN PARAMETERS

DESIGN ASSUMPTIONS	
$P_o = 0.97$	(PROBABILITY OF NO PENETRATION)
$T = 10 \text{ YRS}$	(MISSION DURATION)
$A_d = 574 \text{ m}^2$	(DEBRIS AREA)
$A_m = 403 \text{ m}^2$	(METEOROID AREA)
$Alt = 500 \text{ km}$	(AVERAGE ALTITUDE)
$V_m = 20 \text{ km/sec}$	(AVERAGE METEOROID VELOCITY)
$V_D = 10 \text{ km/sec}$	(AVERAGE DEBRIS VELOCITY)
$\rho_m = 0.5 \text{ gm/cm}^3$	(METEOROID DENSITY)
$\rho_D = 2.81 \text{ gm/cm}^3$	(DEBRIS DENSITY)
$h = 10 \text{ cm}$	(BUMPER/WALL SEPARATION)
NYSMITH EQUATION IDEALIZED SCENARIO	

OPTIMAL DESIGN (BALLISTIC LIMIT)	
$t_{10}$	<u>BUMPER</u> = 0.26 cm (0.10 IN)
$t_{20}$	<u>WALL</u> = 0.48 cm (0.19 IN)

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## DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

SHOWN IS THE OPTIMAL DESIGN, INDUCED BY THE DEBRIS AND METEOROID ENVIRONS, TAKEN SEPARATELY, FOR VARIOUS CORE MODULE SYSTEM AREAS. THE DEBRIS ENVIRONMENT DRIVES DESIGN FOR ALL SYSTEM AREAS. NOTE THE INFLECTION POINT FOR A SYSTEM AREA OF ROUGHLY 850 SQUARE METERS. THIS CORRESPONDS TO THE INFLECTION IN THE DEBRIS ENVIRONMENT CURVE FOR A PARTICLE DIAMETER OF 1 CM. THE EQUIVALENT DEBRIS AREA FOR THE CURRENT DESIGN ("WEIGHT" ~ 0.48 CM) IS ONLY 330 SQUARE METERS.

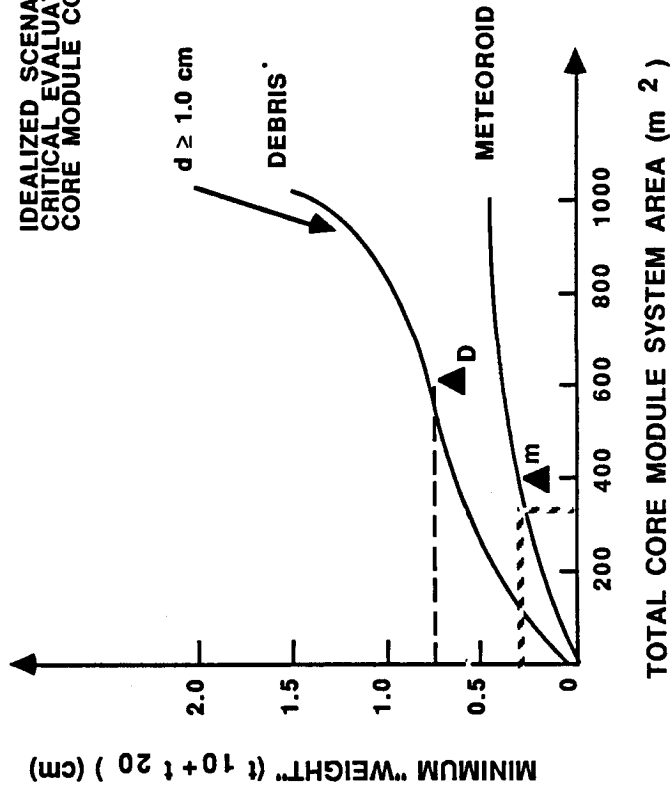
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# DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

EQUIVALENT DEBRIS AREA FOR  
CURRENT DESIGN  $\approx 330\text{M}^2$

IDEALIZED SCENARIO  
CRITICAL EVALUATION TASK FORCE  
CORE MODULE CONFIGURATION



•  $P_0 = 0.97$

- $T = 10$  yrs
- $Alt = 500$  km
- $V_m = 20$  km/sec
- $V_D = 10$  km/sec
- $\rho_m = 0.5$  gm/cm<sup>3</sup>
- $\rho_D = 2.81$  gm/cm<sup>3</sup>
- $h = 10$  cm

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MC8 OT 5/87 RWL

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## DEBRIS ENVIRONMENT DRIVES DESPITE $P_0$ REDUCTION

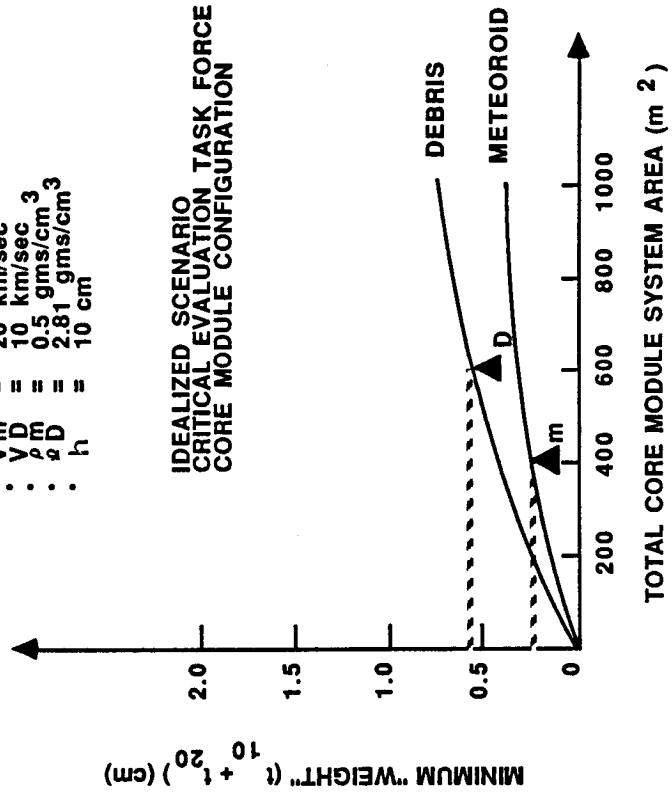
THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A  $P_0$  OF 0.95 IS ILLUSTRATED. ALTHOUGH THIS REDUCTION IN  $P_0$  REPRESENTS A DRAMATIC REDUCTION IN DESIGN, THE DEBRIS ENVIRONMENT CONTINUES TO DRIVE THE DESIGN.

BMI2-9/1

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# DEBRIS ENVIRONMENT DRIVES DESPITE PO REDUCTION

$P_o = 0.95$
$T = 10$ YRS
$Alt = 500$ km
$V_m = 20$ km/sec
$V_D = 10$ km/sec
$\rho_m = 0.5$ gms/cm <sup>3</sup>
$\rho_D = 2.81$ gms/cm <sup>3</sup>
$h = 10$ cm



**INCREASE IN  $P_0$  PRODUCES DRAMATIC WEIGHT  
INCREASE: BASELINE MISSION NOT REALIZED**

SHOWN IS THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A  $P_0$  OF 0.99. CLEARLY, THIS RESULTS IN A SIGNIFICANT INCREASE IN DESIGN TO THE POINT WHERE THE BASELINE SYSTEM AREA CANNOT BE ACHIEVED. THIS IS DUE TO THE FACT THAT THE DESIGN PAR-TICLE INDUCED BY SO LARGE A  $P_0$  EXCEEDS THE LIMITATIONS OF THE THIRD INEQUALITY CONSTRAINT OF NYSMITH.

BM31-9/1

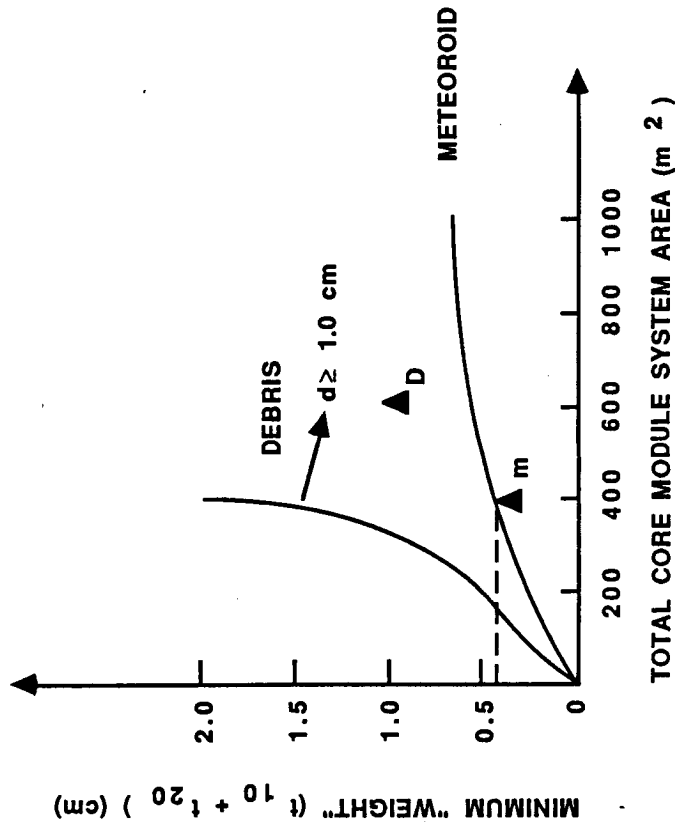
**SAIL**<sup>™</sup>

# INCREASE IN $P_0$ PRODUCES DRAMATIC WEIGHT INCREASE: BASELINE MISSION NOT REALIZED

•  $P_0 = 0.99$

- $T = 10$  YRS
- $Alt = 500$  km
- $V_m = 20$  km/sec
- $V_D = 10$  km/sec
- $\rho_m = 0.5$  gms/cm<sup>3</sup>
- $\rho_D = 2.81$  gms/cm<sup>3</sup>
- $h = 10$  cm

- IDEALIZED SCENARIO
- CRITICAL EVALUATION TASK FORCE  
CORE MODULE CONFIGURATION



UNCLASSIFIED  
MC8 OT 5/87 RWL

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## COMPUTER SOLUTION REGION IS NARROW FOR MOST SCENARIOS - NYSMITH EQUATION

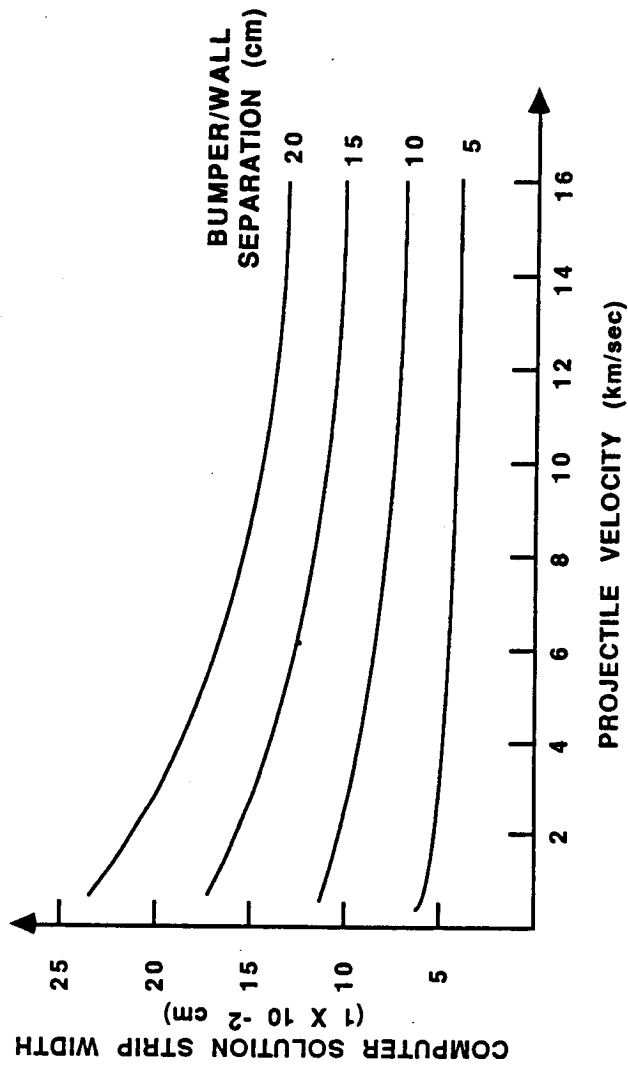
SHOWN IS THE WIDTH OF THE COMPUTER SOLUTION REGION FOR THE NYSMITH EQUATION AS A FUNCTION OF PROJECTILE VELOCITY, FOR VARIOUS BUMPER/WALL SEPARATIONS. THIS WIDTH REPRESENTS THE DIFFERENCE IN THE PROJECTILE DIAMETER AT THE BEGINNING OF THE NO SOLUTION REGION AND THE END OF THE ANALYTICAL SOLUTION REGION. CLEARLY, FOR PARAMETERS IN THE NEIGHBORHOOD OF THE BASELINE PARAMETERS, THIS REGION IS VERY NARROW. IN FACT, THE REGION IS NARROW ENOUGH TO BE APPROXIMATED BY THE ANALYTICAL (UNCONSTRAINED) SOLUTION TO THE NYSMITH EQUATION, THUS REDUCING COMPUTER USAGE.

BM14-9/1

**SAIC**<sup>TM</sup>



# COMPUTER SOLUTION REGION IS NARROW FOR MOST SCENARIOS - NYSMITH EQUATION



UNCLASSIFIED  
MC 9 OT 5/87 RWL

**SAIC**<sup>TM</sup>

## **GP METHOD CONFIRMS THE MINIMUM WEIGHT**

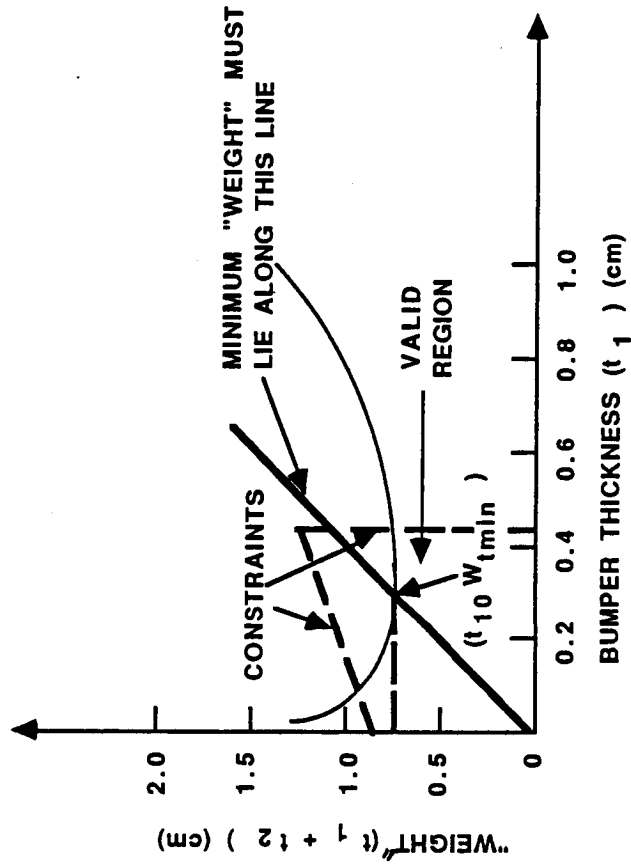
THE BASIC OPTIMIZATION PROBLEM SOLVED USING GEOMETRIC PROGRAMMING (GP) IS SHOWN. THE INTERSECTION OF THE SOLID LINE AND CURVE OCCURS AT THE GLOBAL MINIMUM, VERIFYING THE GP METHODOLOGY. NOTE THAT THE MINIMUM "WEIGHT" LINE DOES NOT INTERSECT THE INTERSECTION OF THE INEQUALITY CONSTRAINTS. THIS OFFSET ESTABLISHES THE COMPUTER SOLUTION REGION AS DISCUSSED EARLIER.

BM15-9/1

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# GP METHOD CONFIRMS THE MINIMUM WEIGHT

- $d = 0.84 \text{ cm}$
- $V = 10 \text{ km/sec}$
- $h = 10 \text{ cm}$
- NYSMITH EQUATION
- IDEALIZED SCENARIO



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MC10 OT 5/87 RWL

**SAIC**

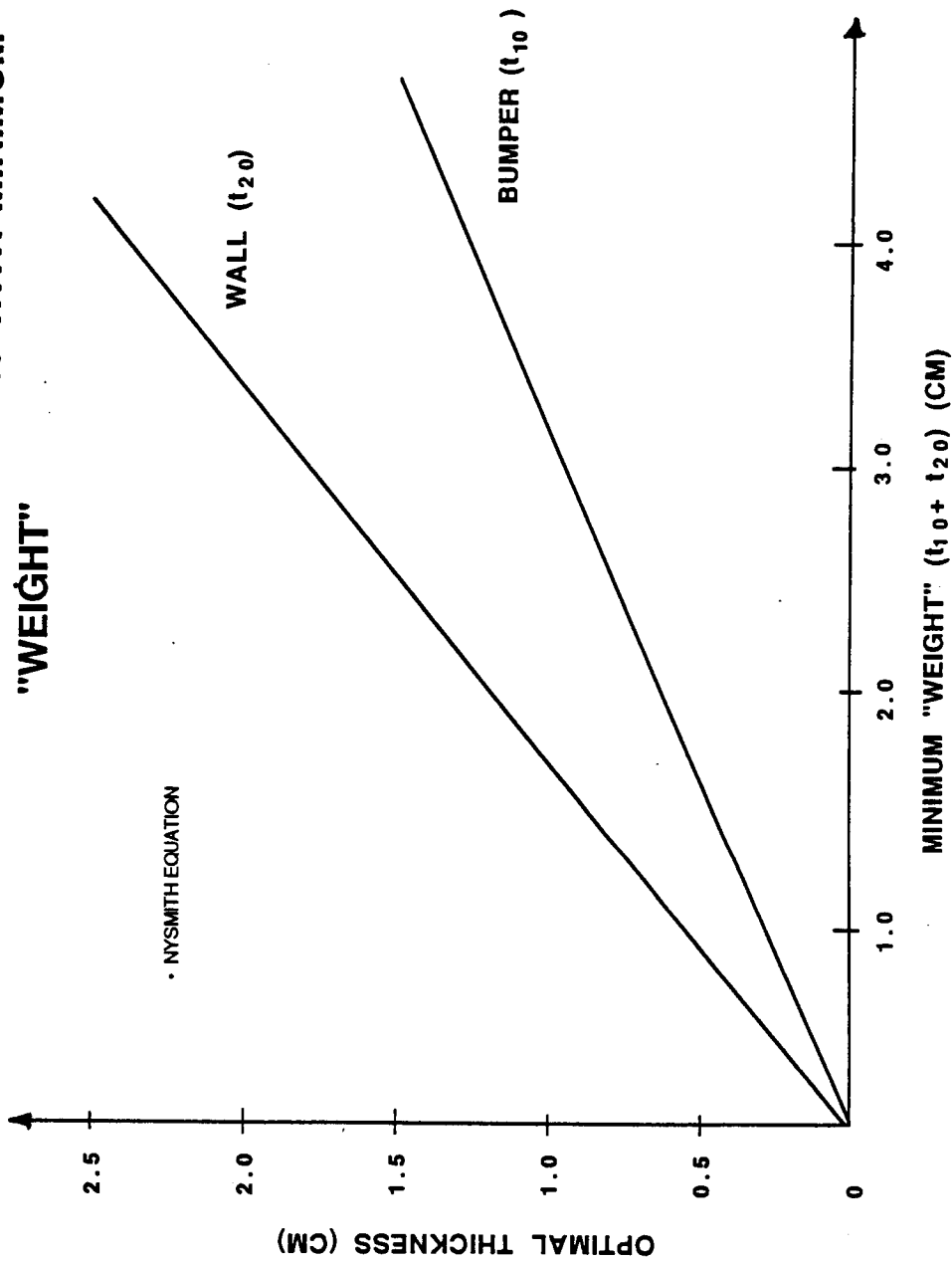
## **OPTIMAL THICKNESSES VARY LINEARLY WITH "MINIMUM WEIGHT"**

SHOWN ARE THE LINEAR RELATIONSHIPS BETWEEN THE OPTIMAL THICKNESSES OF THE BUMPER AND WALL AND THE MINIMUM "WEIGHT" AS REPRESENTED BY THE SUM OF BUMPER AND WALL THICKNESSES. THE LINES, EMANATING FROM THE ORIGIN, HAVE SLOPES OF 0.35 AND 0.65 FOR THE BUMPER AND WALL, RESPECTIVELY.

BM16-9/1

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# OPTIMAL THICKNESSES VARY LINEARLY WITH MINIMUM "WEIGHT"



2 OT RLK

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## **OPTIMAL WALL THICKNESS VARIES LINEARLY WITH OPTIMAL BUMPER THICKNESS**

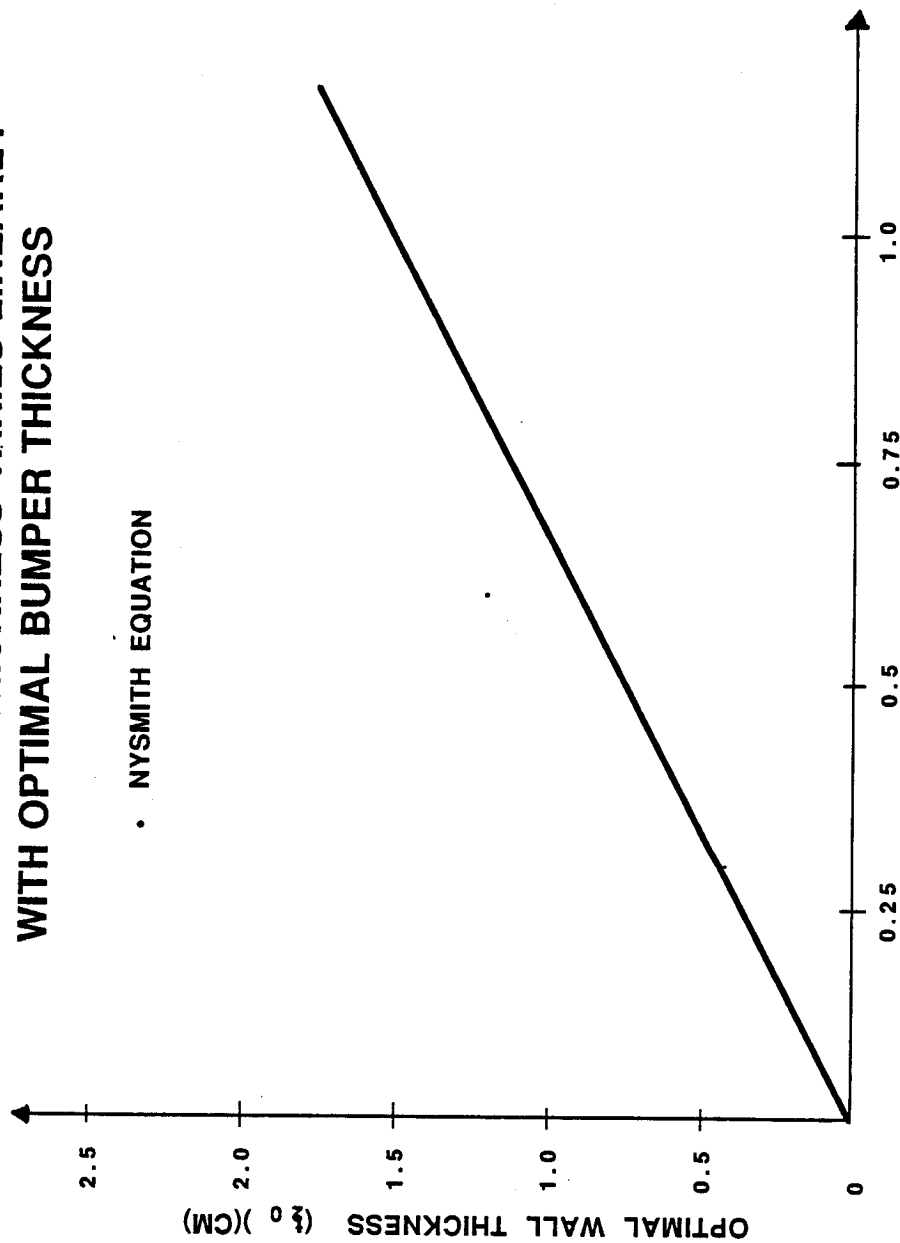
**SHOWN IS THE LINEAR RELATIONSHIP BETWEEN THE OPTIMAL WALL THICKNESS AND THE OPTIMAL BUMPER THICKNESS FOR THE NYSMITH PREDICTOR. THE LINE EMANATES FROM THE ORIGIN AND HAS A SLOPE OF APPROXIMATELY 1.92.**

BM17-9/1

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# OPTIMAL WALL THICKNESS VARIES LINEARLY WITH OPTIMAL BUMPER THICKNESS

• NYSMITH EQUATION



UNCLASSIFIED  
MC11 OT RWL

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## OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

THIS SET OF CURVES SHOWS THE EFFECT OF BUMPER/WALL SEPARATION ON OPTIMAL DESIGN FOR THE NYSMITH PREDICTOR. NOTE THE HIGH PAY-OFF FOR INCREASING THIS SEPARATION UP TO ABOUT 15 CM, WHICH, INCIDENTALLY, CORRESPONDS TO THE CORE MODULE VOLUME CONSTRAINT FOR SHUTTLE PAYLOADS. FINALLY, TOWARD THE LEFT OF THE THREE CURVES LIE THE CONSTRAINTS IMPOSED ON THIS SEPARATION BY THE THIRD INEQUALITY CONSTRAINT OF THE NYSMITH EQUATION. NOTE THAT THESE POINTS LIE ON A STRAIGHT LINE THROUGH THE ORIGIN, AND THE REGION TO THE LEFT OF THIS LINE IS INFEASIBLE.

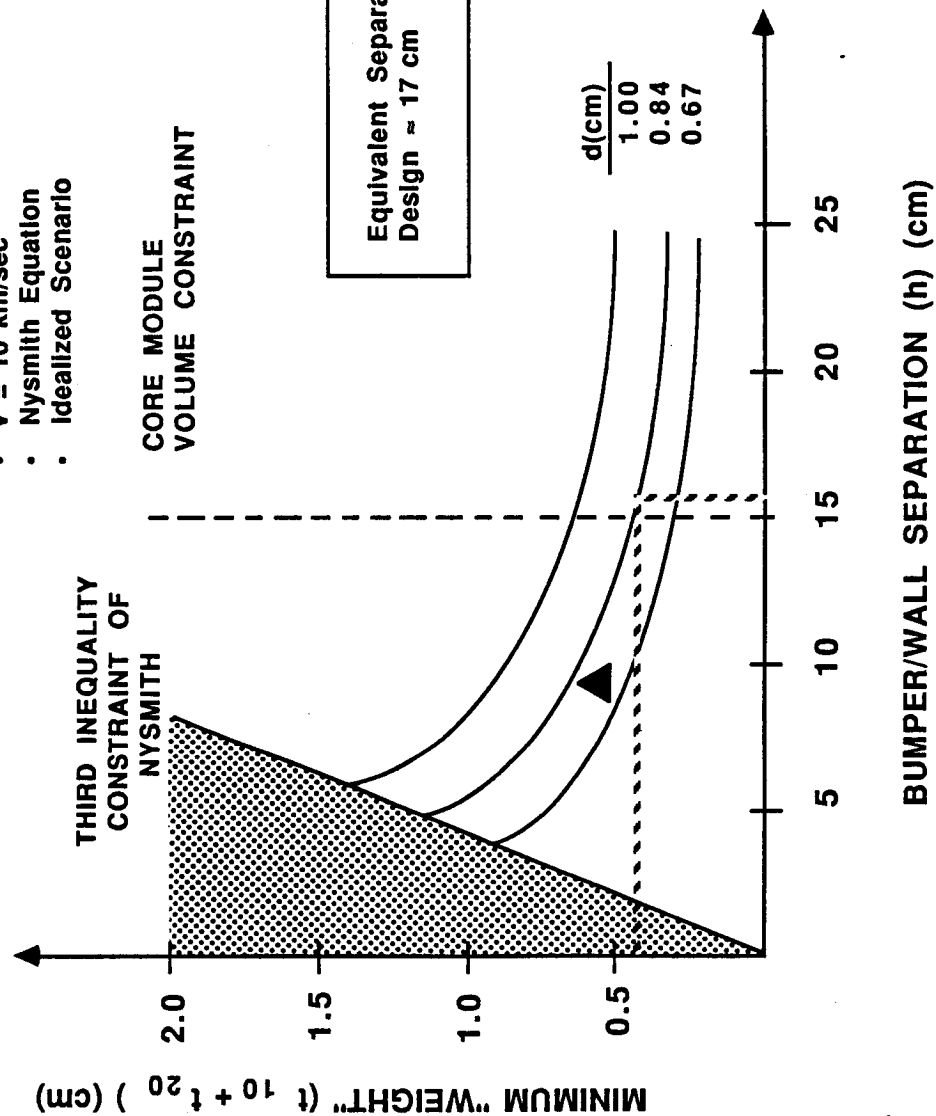
BM18-9/1

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# OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

- $V = 10 \text{ km/sec}$
- Nysmith Equation
- Idealized Scenario



Equivalent Separation for Current Design  $\approx 17 \text{ cm}$

## **GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN**

ONE IMPORTANT SENSITIVITY ANALYSIS IS THE EFFECT OF THREAT, IN TERMS OF SPACE DEBRIS PROJECTILE DIAMETER, ON OPTIMAL DESIGN.

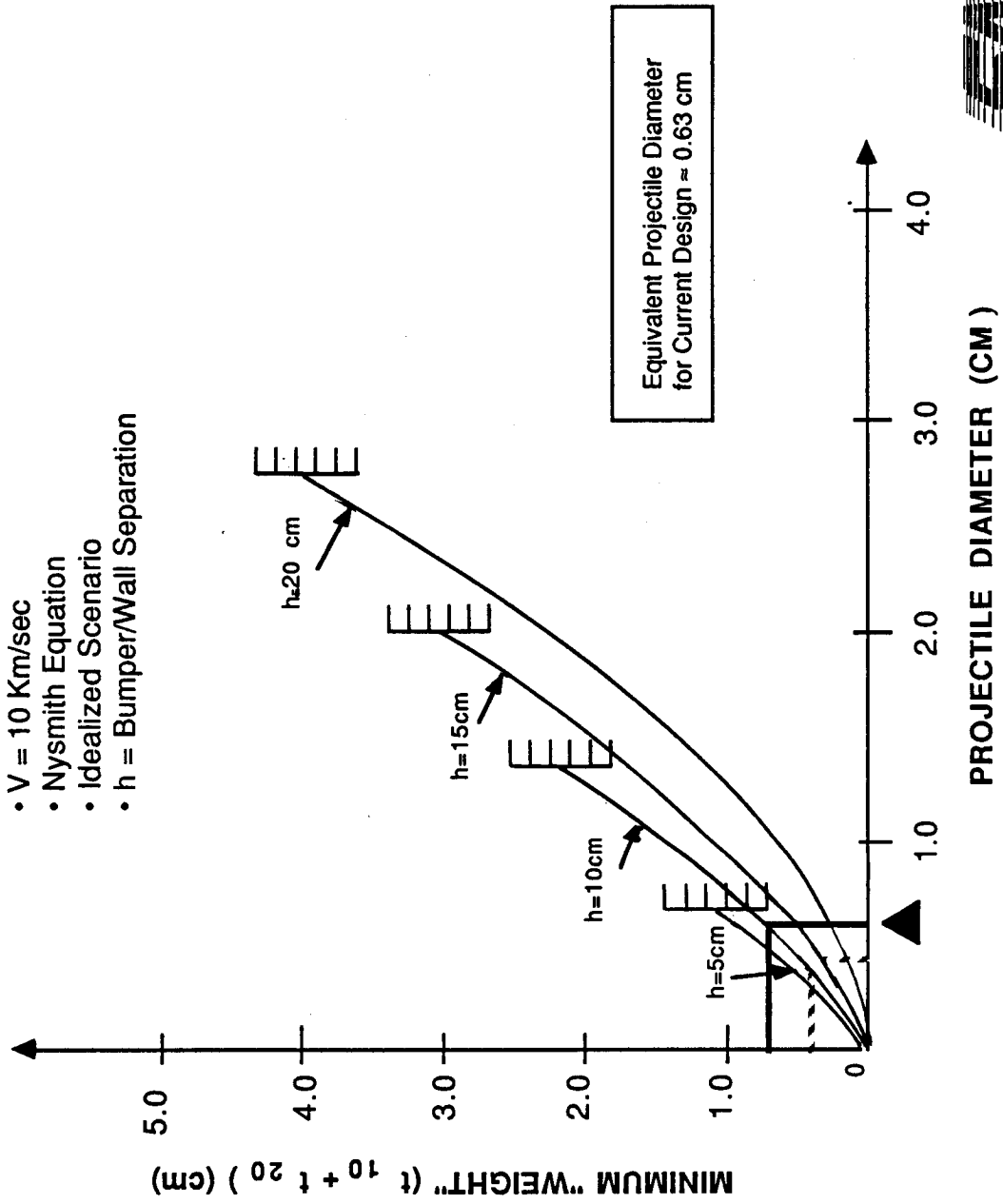
THE EFFECT OF PROJECTILE DIAMETER ON "WEIGHT" IS SHOWN FOR VARIOUS BUMPER/WALL SEPARATIONS. THE EQUIVALENT PROJECTILE DIAMETER INDUCED BY THE CURRENT DESIGN IS ROUGHLY 0.63 CM. THE LIMITS IMPOSED ON PROJECTILE DIAMETER BY THE THIRD INEQUALITY CONSTRAINT FOR EACH CURVE ARE SHOWN TO THE RIGHT. AGAIN, THESE CURVES LIE ON A STRAIGHT LINE THROUGH THE ORIGIN.

BM19-9/1

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# GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN

- $V = 10 \text{ Km/sec}$
- Nysmith Equation
- Idealized Scenario
- $h = \text{Bumper/Wall Separation}$



## **OPTIMAL DESIGN IS SENSITIVE TO THREAT**

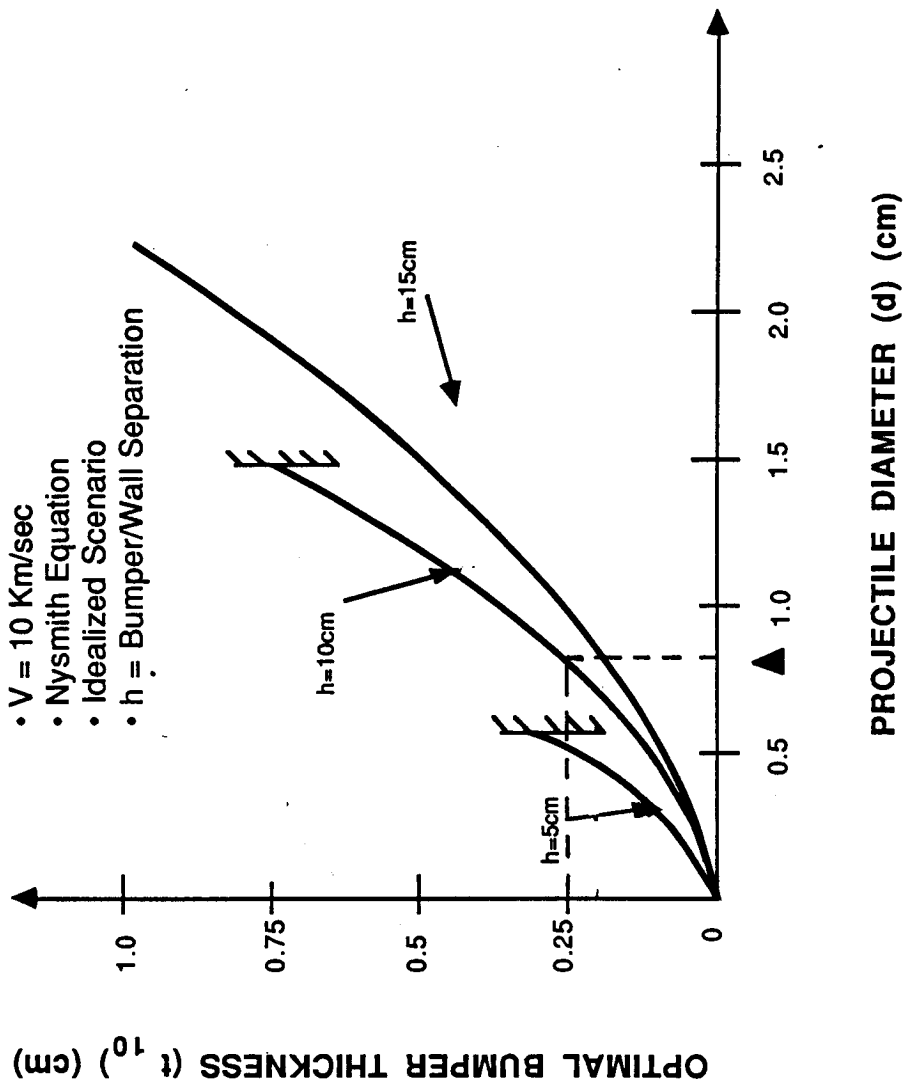
**THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER THICKNESS IS SHOWN. A 20% INCREASE IN DIAMETER ABOVE THE BASELINE REQUIRES A 40% INCREASE IN OPTIMAL BUMPER THICKNESS.**

BM20-9/1

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# OPTIMAL DESIGN IS SENSITIVE TO THREAT

- $V = 10 \text{ Km/sec}$
- Nysmith Equation
- Idealized Scenario
- $h = \text{Bumper/Wall Separation}$



# **OPTIMAL DESIGN IS SENSITIVE TO THREAT**

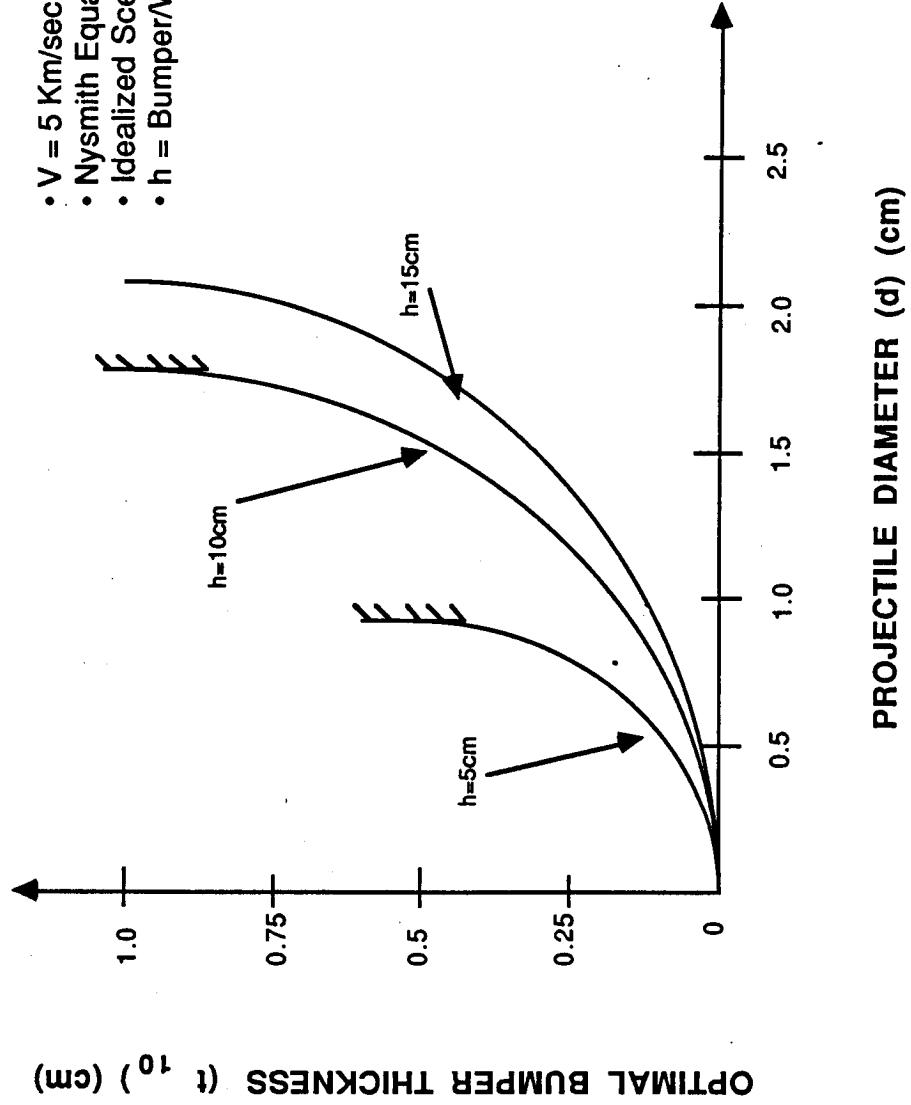
**THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER THICKNESS FOR A PROJECTILE VELOCITY OF 5 KM/SEC IS SHOWN.**

BM21-9/1



# OPTIMAL DESIGN IS SENSITIVE TO THREAT

- $V = 5 \text{ Km/sec}$
- Nysmith Equation
- Idealized Scenario
- $h = \text{Bumper/Wall Separation}$



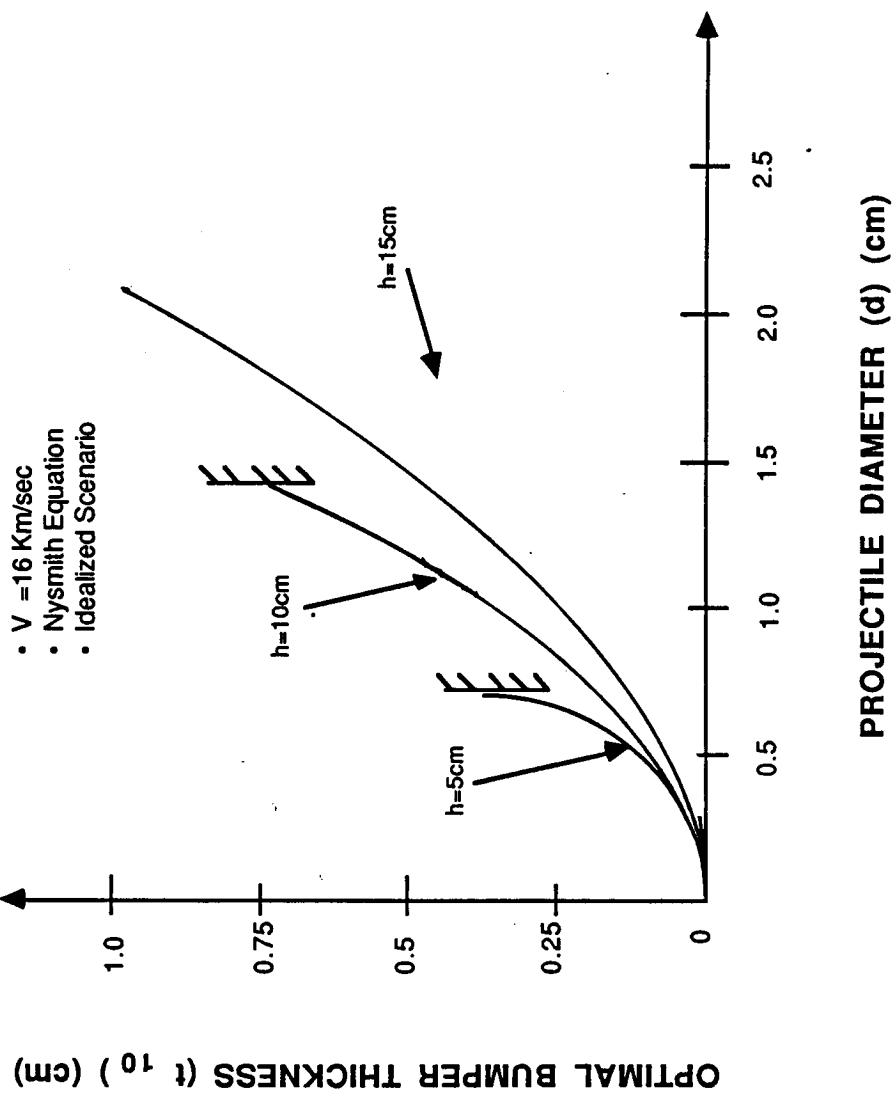
**OPTIMAL DESIGN IS SENSITIVE TO THREAT  
THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER  
THICKNESS FOR A PROJECTILE VELOCITY OF 16 KM/SEC IS  
SHOWN.**

BM22-9/1

**SAIC**



## OPTIMAL DESIGN IS SENSITIVE TO THREAT



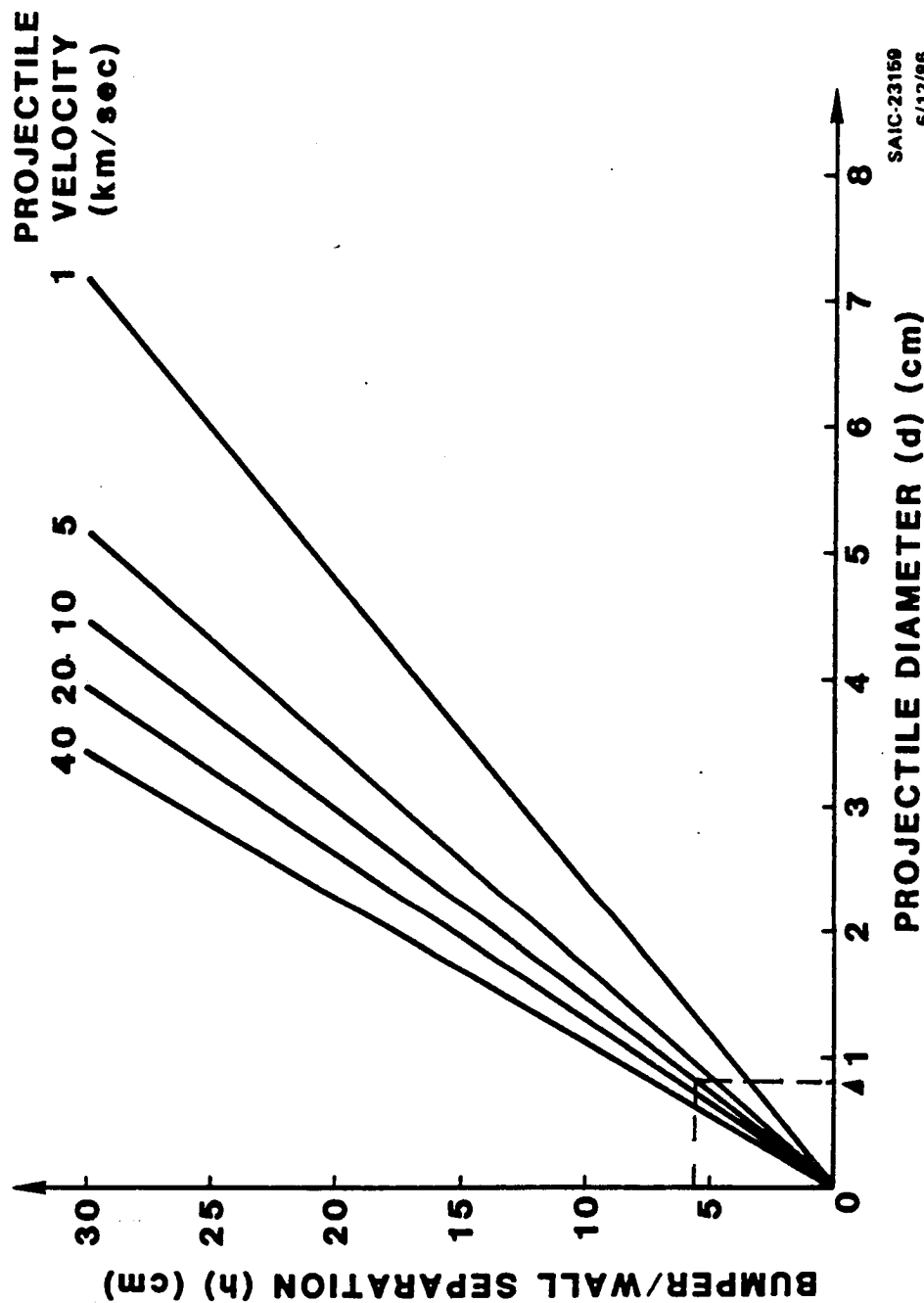
**GP METHOD PROVIDES THE MINIMUM BUMPER/WALL  
SEPARATION REQUIRED FOR VARIOUS THREAT SCENARIOS**

**THE THIRD INEQUALITY CONSTRAINT OF THE NYSMITH EQUATION IN TERMS  
OF THE MINIMUM BUMPER/WALL SEPARATION AS A FUNCTION OF PROJECTILE  
DIAMETER FOR VARIOUS PROJECTILE VELOCITIES IS SHOWN. THE BASELINE  
MINIMUM SEPARATION ALLOWED IS ROUGHLY 6 CM.**

BM23-9/1

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# GP METHOD PROVIDES THE MINIMUM BUMPER/WALL SEPARATION REQUIRED FOR VARIOUS THREAT SCENARIOS



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6/12/86

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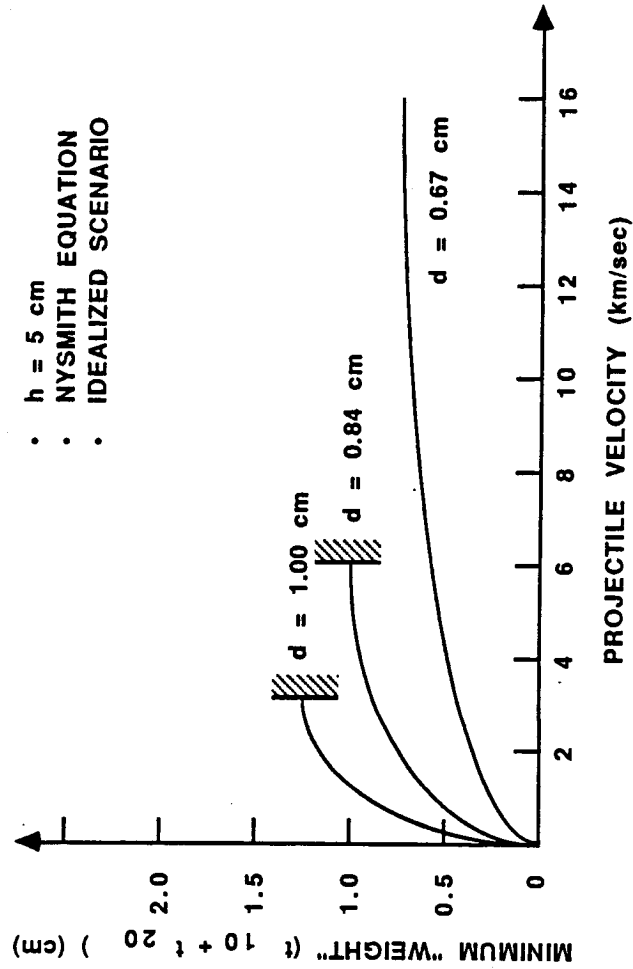
## OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

THE NEXT THREE TRADE SETS SHOW THE EFFECT OF PROJECTILE VELOCITY ON DESIGN FOR VARIOUS PROJECTILE DIAMETERS, FOR 5, 10, AND 15 CM BUMPER/WALL SEPARATIONS. IN THE HIGHER VELOCITY (5-16 KM/SEC) PORTIONS OF THESE CURVES, THE DESIGN REMAINS RELATIVELY INSENSITIVE TO PROJECTILE VELOCITY. NOTE THAT THE EQUIVALENT PROJECTILE VELOCITY INDUCED BY THE CURRENT DESIGN IS 2.5 KM/SEC.

BM24-9/1

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# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS



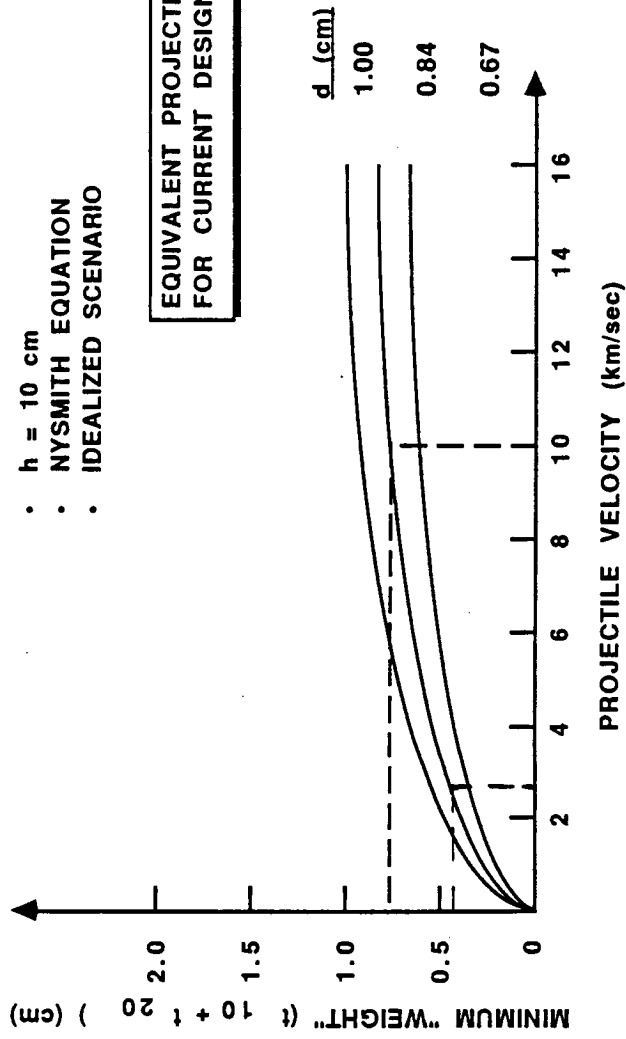
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MC 12 OT 5/87 RWL

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# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS



- h = 10 cm
- NYSMITH EQUATION
- IDEALIZED SCENARIO

EQUIVALENT PROJECTILE VELOCITY  
FOR CURRENT DESIGN~ 2.5 km/sec

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MC 13 OT 5/87 RWL

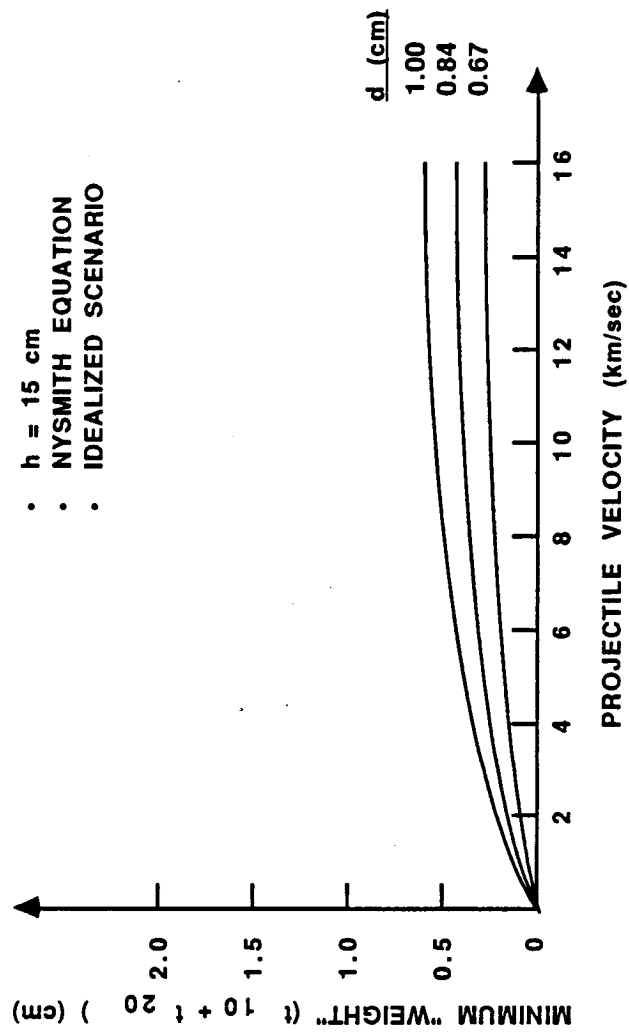
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# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS



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MC 14 OT 5/87 RWL

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**OPTIMAL DESIGN IS HIGHLY SENSITIVE TO  
MISSION RISK FOR  $P_0$  ABOVE 0.97**

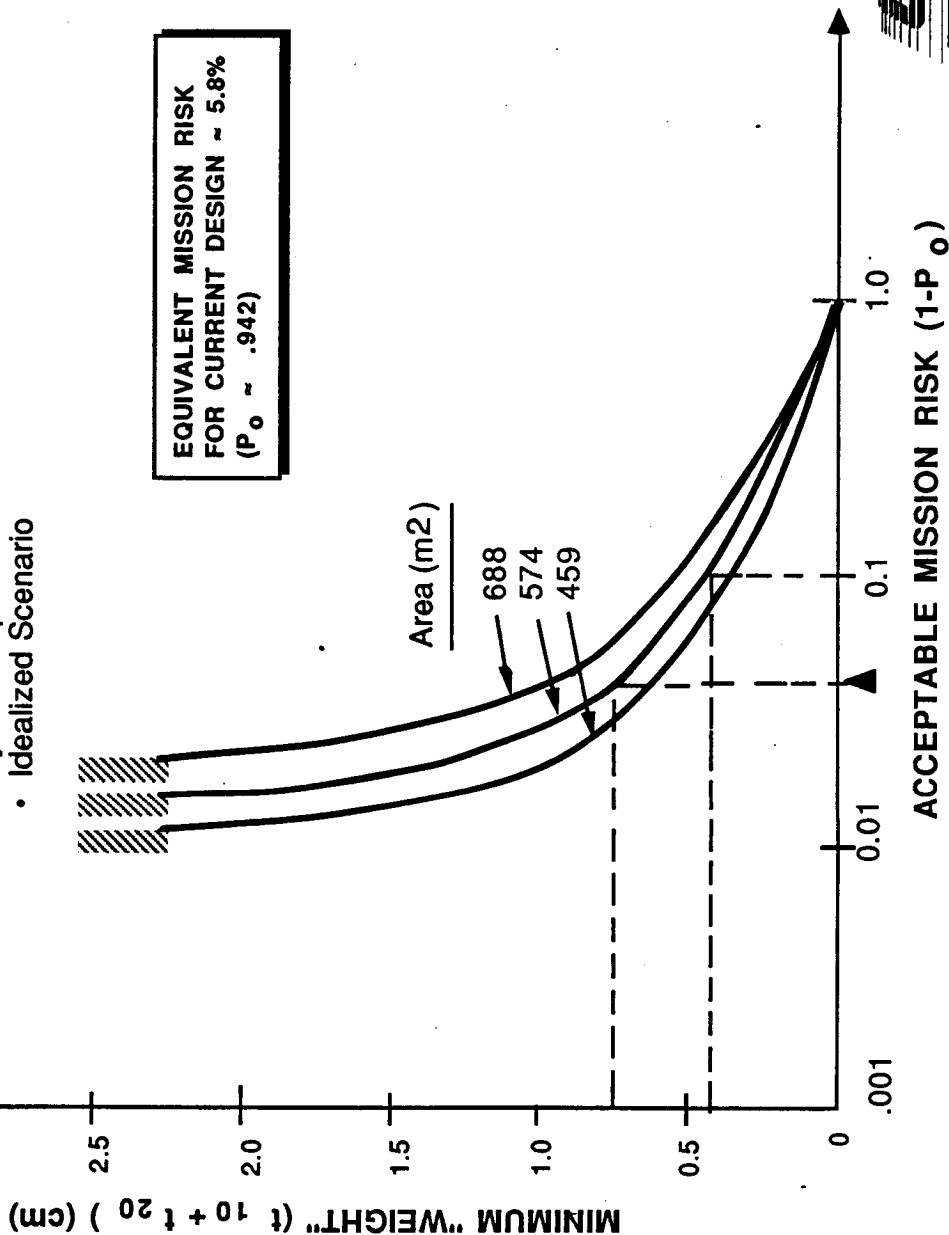
**THE EFFECT OF DESIGN ON ACCEPTABLE MISSION RISK FOR VARIOUS  
SPACECRAFT DEBRIS AREAS, AND FOR VARIOUS BUMPER/WALL  
SEPARATIONS IS SHOWN IN THE NEXT THREE CHARTS. MISSION RISK  
PLAYS A VERY SIGNIFICANT ROLE IN DETERMINING THE OPTIMAL DESIGN.  
NOTE THAT THE EQUIVALENT MISSION RISK INDUCED BY THE CURRENT  
DESIGN IS 5.8%, CORRESPONDING TO A  $P_0$  OF 0.942.**

BM25-9/1

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# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_o$ ABOVE 0.97

- $V = 10\text{Km/sec}$
- $T = 10$  years
- $h = 10$  cm
- Nysmith Equation
- Idealized Scenario



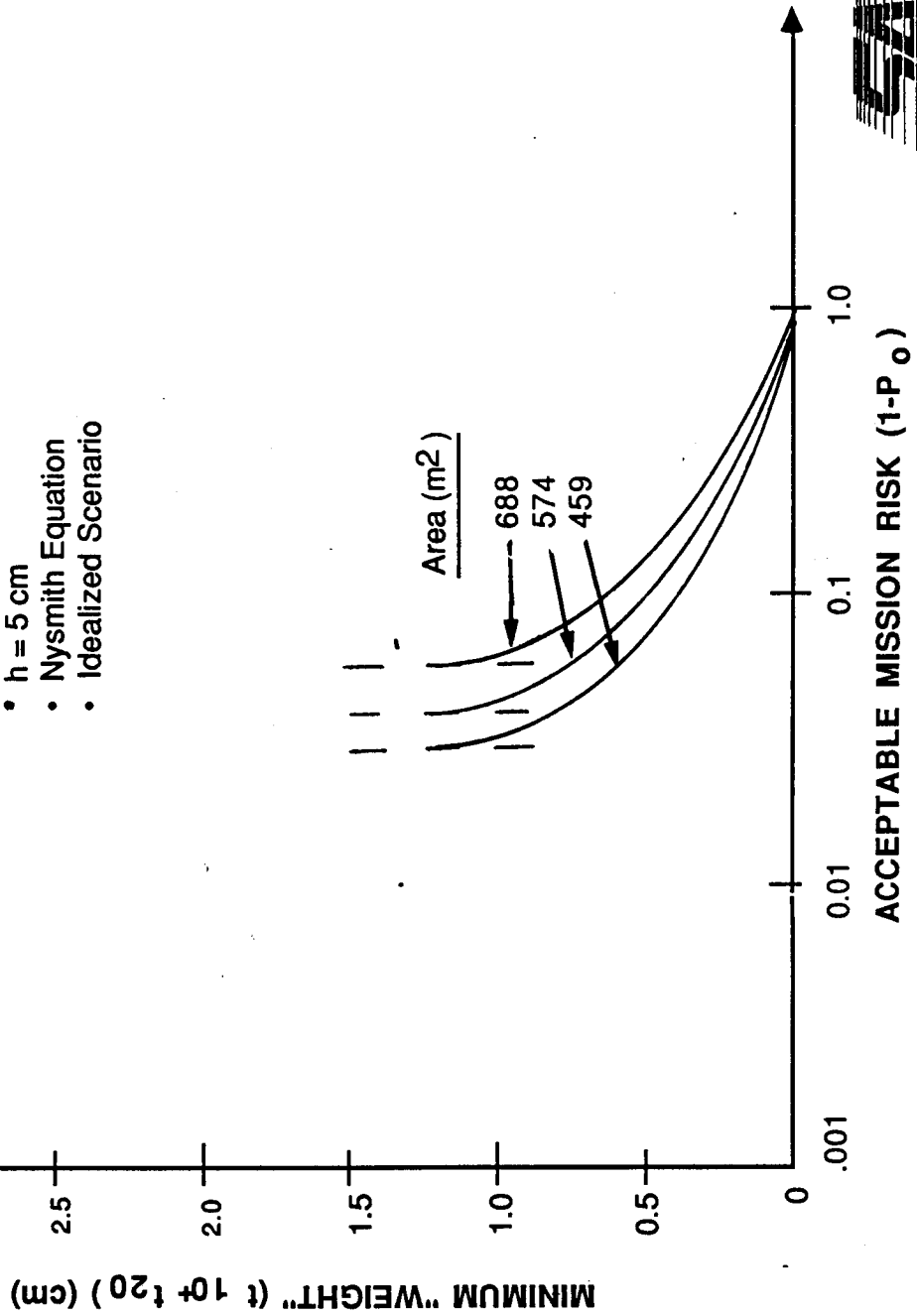
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OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK  
FOR  $P_0$  ABOVE 0.97

- $V = 10 \text{ Km/sec}$
- $T = 10 \text{ years}$
- $h = 5 \text{ cm}$
- Nysmith Equation
- Idealized Scenario

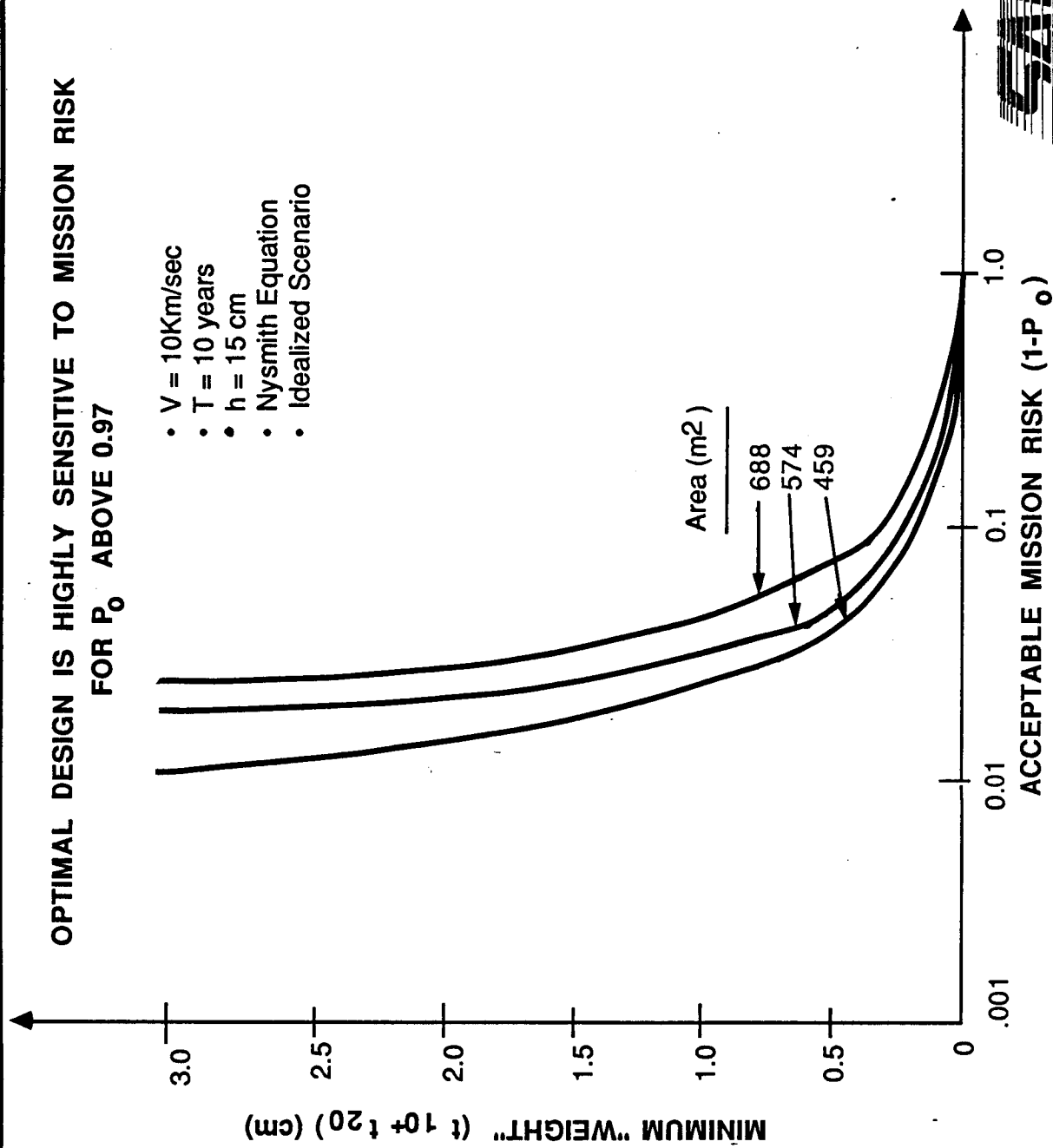


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# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_o$ ABOVE 0.97

- $V = 10\text{Km/sec}$
- $T = 10\text{ years}$
- $h = 15\text{ cm}$
- Nysmith Equation
- Idealized Scenario



## OPTIMAL DESIGN IS SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

THE NEXT TWO SETS OF TRADES SHOW, FOR DIFFERENT  $P_0$ 'S, THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR VARIOUS SPACECRAFT DEBRIS AREAS. NOTE THE HIGH SENSITIVITY, EVEN INFLECTION IN SOME CASES, OCCURRING IN THE 10-30 YEAR RANGE. THE INFLECTION IS DUE TO THE INFLECTION IN THE SPACE DEBRIS ENVIRONMENT CURVE AT 1 CM DIAMETER PARTICLES. THE EQUIVALENT MISSION DURATION FOR THE CURRENT DESIGN IS ROUGHLY 5.5 YEARS.

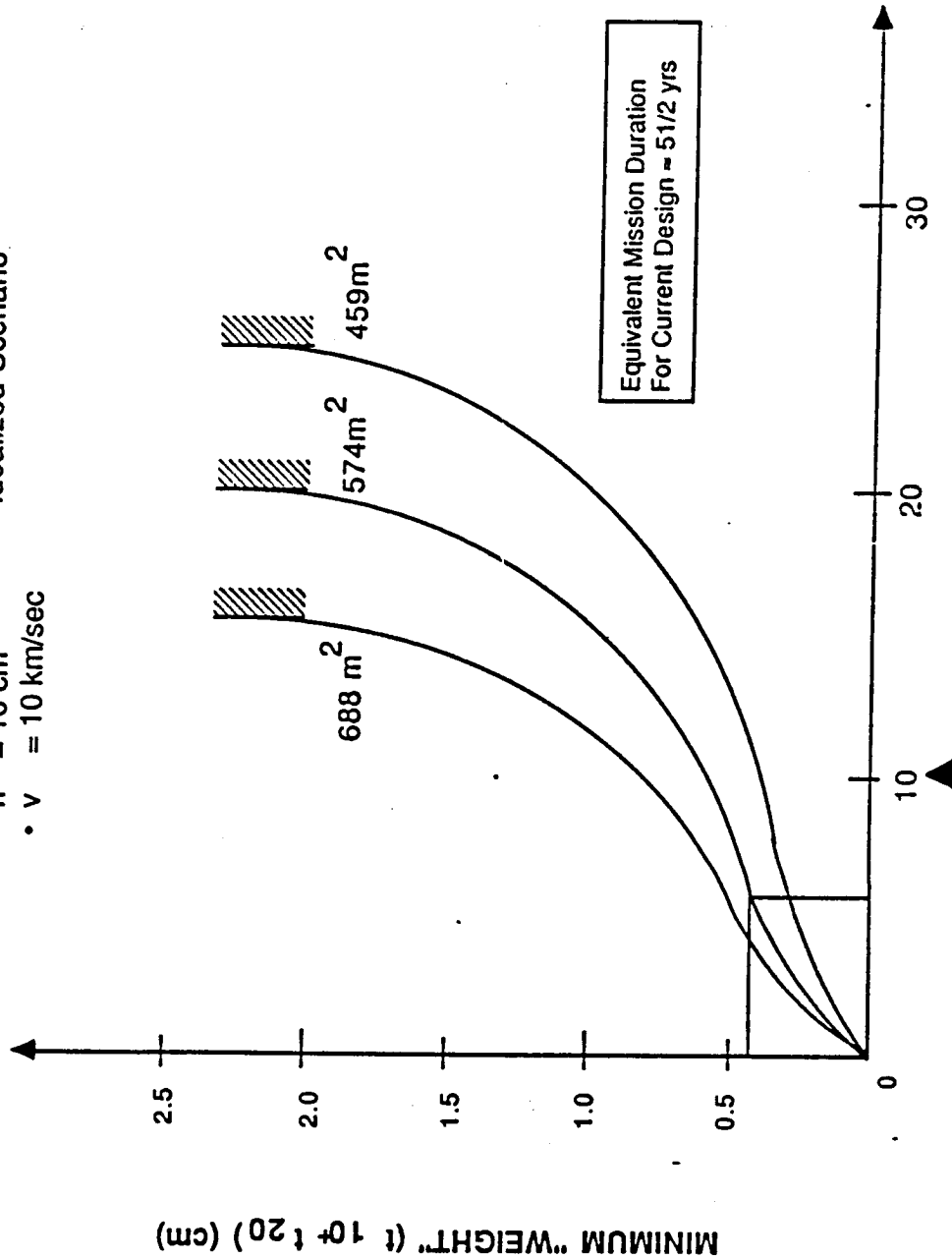
BM26-9/1

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# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

- $P_0 = 0.97$
- $h = 10 \text{ cm}$
- $v = 10 \text{ km/sec}$
- Nysmith Equation
- Idealized Scenario



**SAIC**

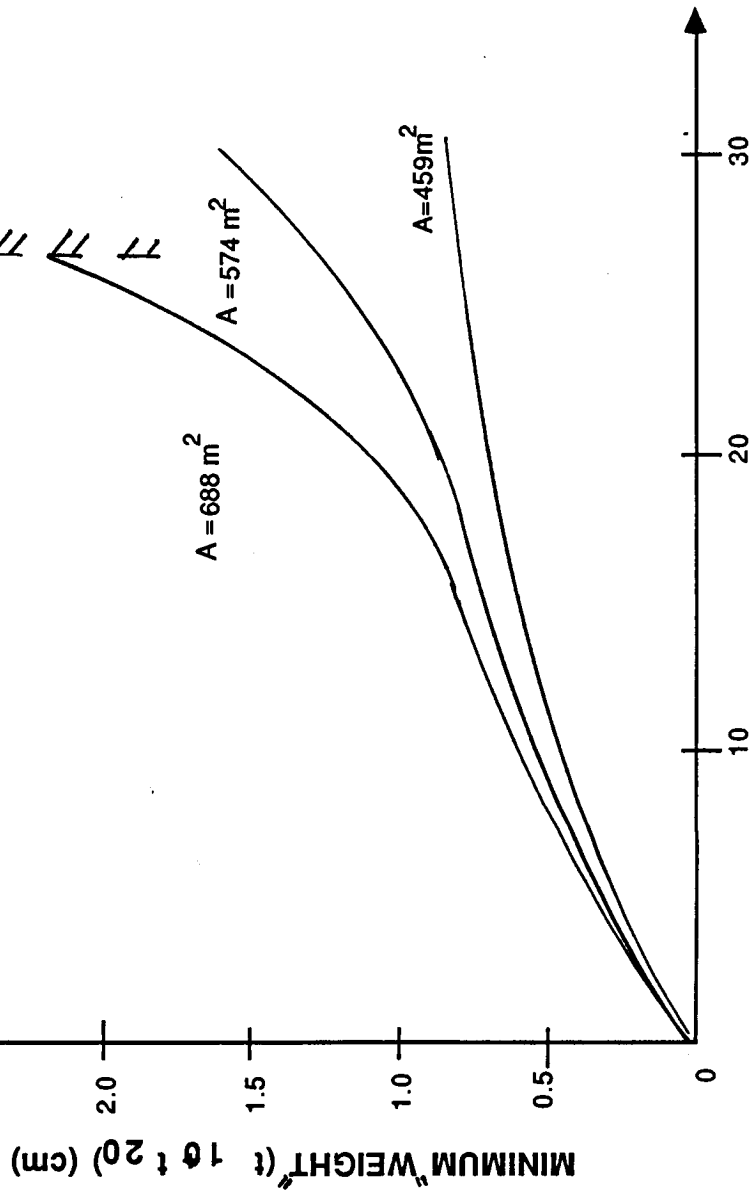
MISSION DURATION (T) (yrs)

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# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

- $P_0 = 0.95$
- $h = 10 \text{ cm}$
- $V = 10 \text{ km/sec}$
- Nysmith Equation
- Idealized Scenario



MISSION DURATION (T) (yrs)



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# **SECTION III**

## **NYSMITH PREDICTOR APPLIED TO CORE MODULE CONFIGURATION**

BM40-9/1

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## WHAT YOU WILL SEE IN SECTION III

- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE NYSMITH PREDICTOR APPLIED TO THE CORE MODULE CONFIGURATION
- DESIGN TRADES, INCLUDING MINIMUM WEIGHT VERSUS:
  - BUMPER/WALL SEPARATION
  - PROJECTILE DIAMETER
  - PROJECTILE VELOCITY
  - MISSION RISK
  - MISSION DURATION

BM3 10/13

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## **BASELINE CORE MODULE CONFIGURATION**

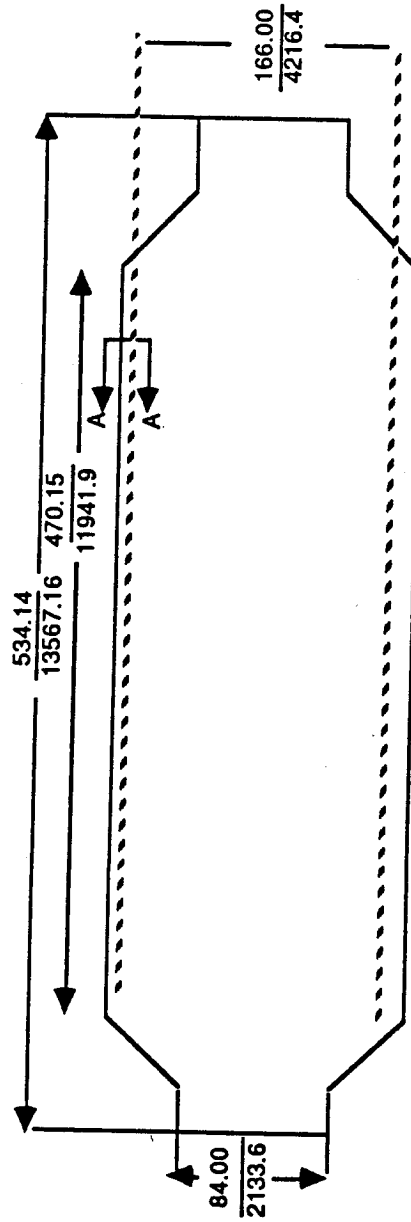
**SHOWN IS THE MARCH 1987 CORE MODULE CONFIGURATION. THIS IS USED TO OBTAIN THE OBJECTIVE FUNCTION WHICH ESTIMATES ITS WEIGHT.**

BM27-9/1

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# BASELINE CORE MODULE CONFIGURATION



• TOP DIMENSIONS IN INCHES

• BOTTOM DIMENSIONS IN MILLIMETERS



## **DESIGN ERROR INDUCED BY REDUCING PROBLEM DEGREE-OF-DIFFICULTY IS NEGLIGIBLE**

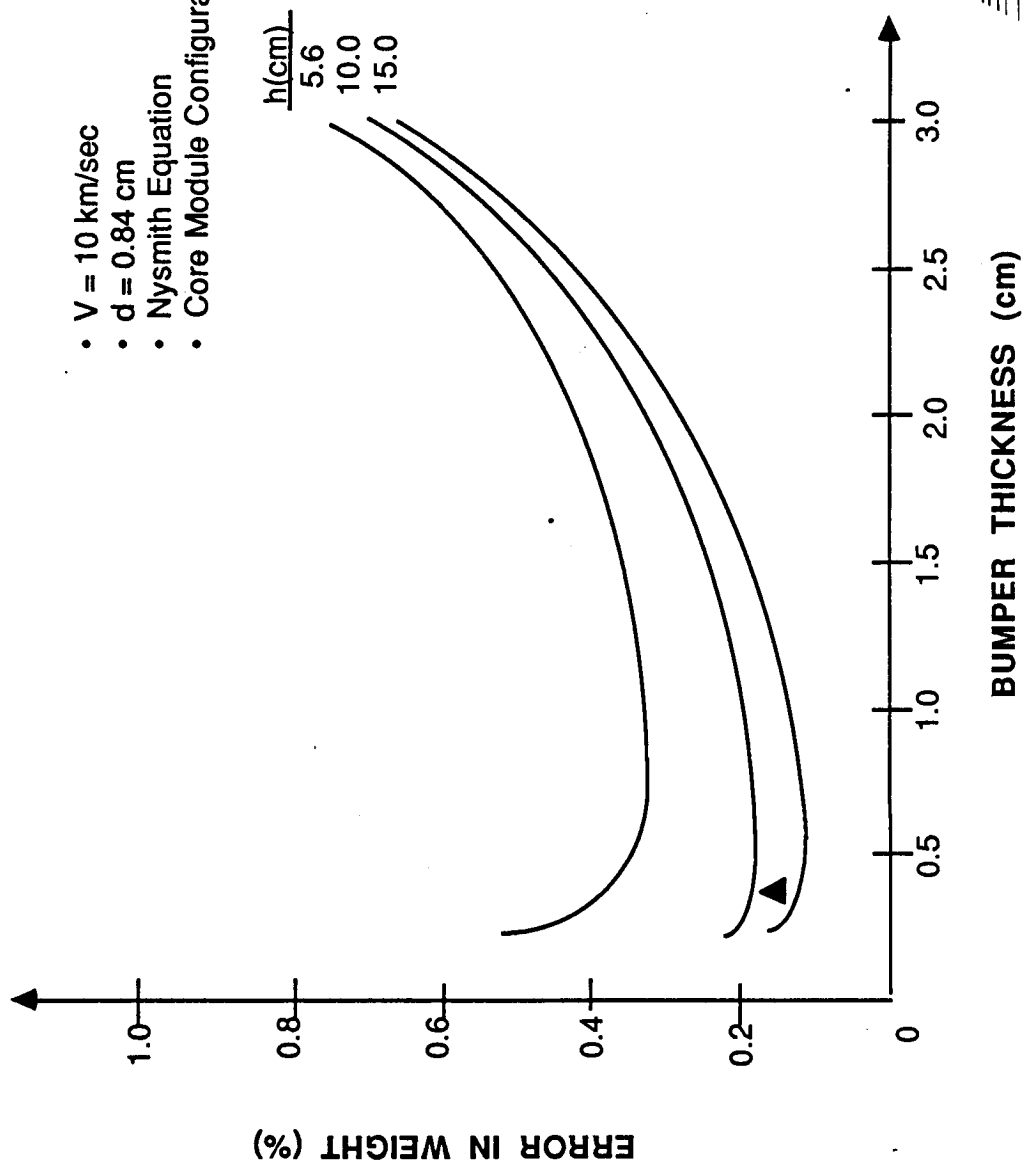
SHOWN IS THE ERROR IN THE CORE MODULE CONFIGURATION WEIGHT AS A FUNCTION OF BUMPER THICKNESS FOR VARIOUS BUMPER/WALL SEPARATIONS. THIS REPRESENTS THE ERROR INDUCED BY REDUCING THE OPTIMIZATION PROBLEM DEGREE-OF-DIFFICULTY FROM 5 TO 2. THIS ERROR WILL BE NEGLIGIBLE PROVIDED THE BUMPER AND WALL THICKNESSES ARE SMALL IN COMPARISON TO THE MODULE RADIUS. THE MATHEMATICS BEHIND THIS REDUCTION IN DEGREE-OF-DIFFICULTY IS GIVEN IN APPENDIX A.

BM28-9/1

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**DESIGN ERROR INDUCED BY REDUCING PROBLEM  
DEGREE-OF-DIFFICULTY IS NEGLIGIBLE**

- $V = 10 \text{ km/sec}$
- $d = 0.84 \text{ cm}$
- Nysmith Equation
- Core Module Configuration



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## BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS ARE REFERENCED. THE OPTIMAL DESIGN IS ALMOST EXACTLY THE SAME AS THAT FOUND USING THE IDEALIZED SCENARIO AS THE OBJECTIVE FUNCTION. THIS, COMBINED WITH THE PRECEDING ERROR SHEET, MAKES IT DESIRABLE TO DETERMINE THE OPTIMAL DESIGN VALUES FROM THE IDEALIZED SCENARIO, AND THEN EVALUATE THE CORE MODULE CONFIGURATION WEIGHT USING THOSE VALUES. NOTE THAT THE BASELINE WEIGHT IS ROUGHLY 3800 Kg, OR 8400 LBS.

BM01-8/31

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# BASELINE DESIGN PARAMETERS

DESIGN	PARAMETERS
$P_o$	= 0.97
$T$	= 10 YRS
$A_d$	= 574 m <sup>2</sup>
$A_m$	= 403 m <sup>2</sup>
$Alt$	= 500 km
$V_m$	= 20 km/sec
$V_D$	= 10 km/sec
$\rho_m$	= 0.5 gm/cm <sup>3</sup>
$\rho_D$	= 2.81 gm/cm <sup>3</sup>
$h$	= 10 cm
NYSMITH EQUATION	

OPTIMAL DESIGN (BALLISTIC LIMIT)	
<u>BUMPER</u>	
$t_{10}$	= 0.26 cm (0.10 IN)
<u>WALL</u>	
$t_{20}$	= 0.48 cm (0.19 IN)
WEIGHT ~ 3800 Kg (8400 lbs)	

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## DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

THE OPTIMAL DESIGN, INDUCED BY THE DEBRIS AND METEOROID ENVIRONS, TAKEN SEPARATELY, FOR VARIOUS CORE MODULE SYSTEM AREAS IS SHOWN. THE DEBRIS ENVIRONMENT DOMINATES THAT OF THE METEOROID FOR ALL SYSTEM AREAS. NOTE THE INFLECTION POINT FOR A SYSTEM AREA OF ROUGHLY 850 SQUARE METERS. THIS CORRESPONDS TO THE INFLECTION IN THE DEBRIS ENVIRONMENT CURVE FOR A PARTICLE DIAMETER OF 1 CM.

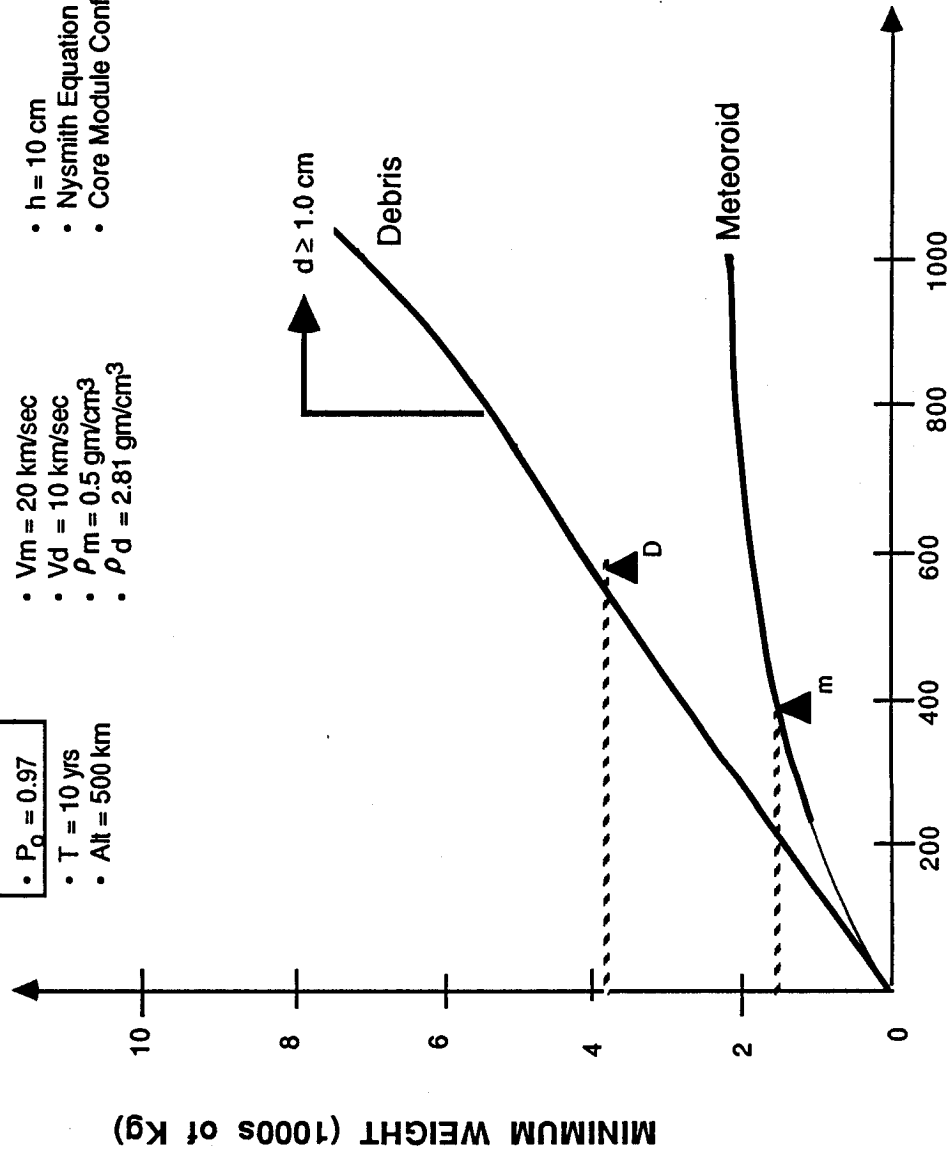
BM29-9/1

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# DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

- $P_0 = 0.97$
  - $T = 10$  yrs
  - Alt = 500 km

- $V_m = 20$  km/sec
  - $V_d = 10$  km/sec
  - $\rho_m = 0.5$  gm/cm<sup>3</sup>
  - $\rho_d = 2.81$  gm/cm<sup>3</sup>
- $h = 10$  cm
  - Nysmith Equation
  - Core Module Configuration



TOTAL CORE MODULE SYSTEM AREA (m<sup>2</sup>)

## DEBRIS ENVIRONMENT DRIVES DESPITE $P_0$ REDUCTION

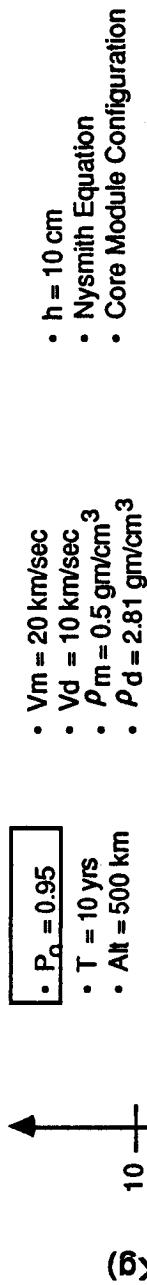
THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A  $P_0$  OF 0.95 IS SHOWN. ALTHOUGH THIS REDUCTION IN  $P_0$  REPRESENTS A DRAMATIC REDUCTION IN DESIGN, THE DEBRIS ENVIRONMENT CONTINUES TO DRIVE THE DESIGN.

BM30-9/1

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# DEBRIS ENVIRONMENT DRIVES DESPITE $P_0$ REDUCTION



**SAIL**

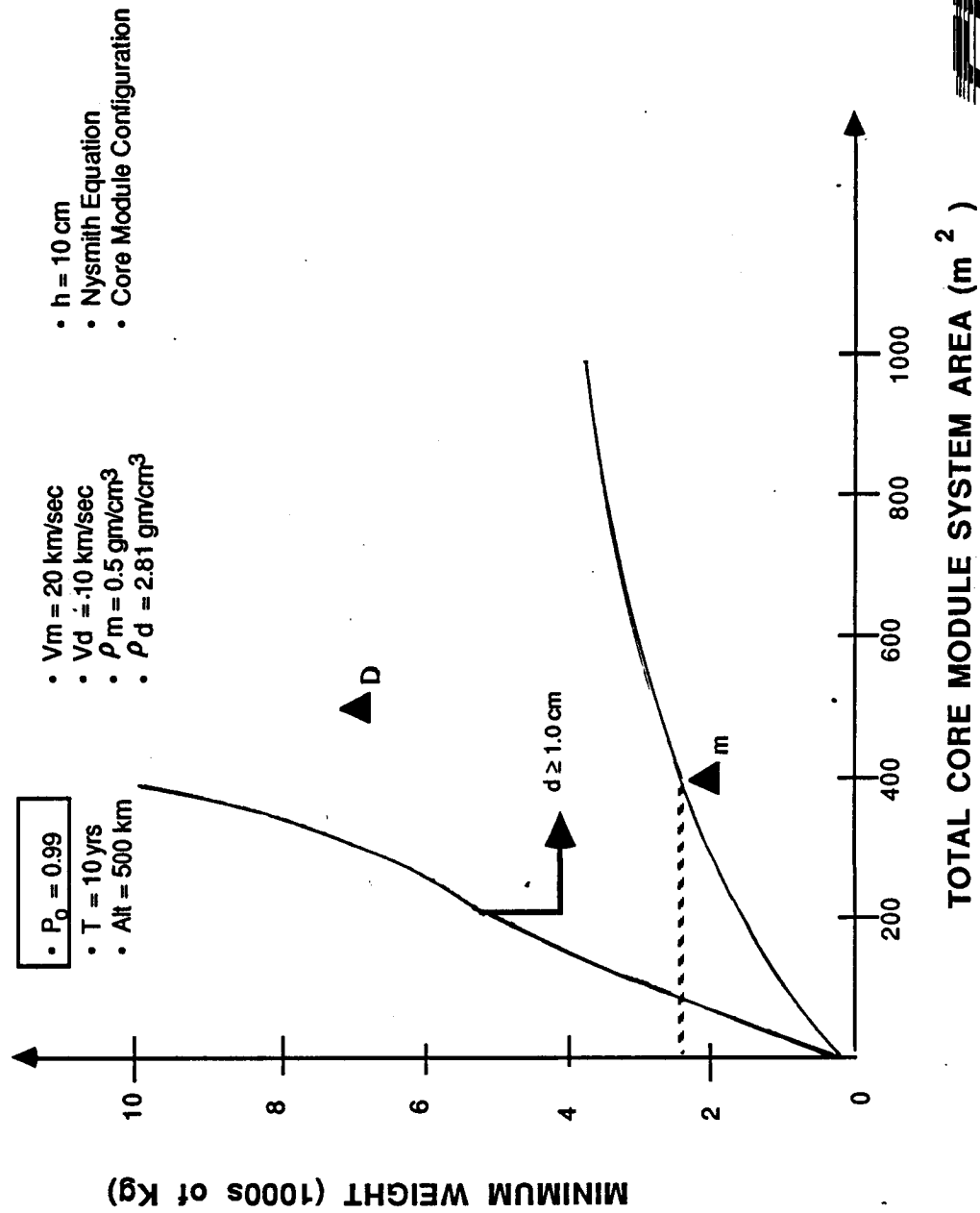
**INCREASE IN  $P_0$  PRODUCES DRAMATIC WEIGHT INCREASE:  
BASELINE MISSION NOT REALIZED.**

THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A  $P_0$  OF 0.99 IS SHOWN. CLEARLY, THIS RESULTS IN A SIGNIFICANT INCREASE IN DESIGN TO THE POINT WHERE THE BASELINE SYSTEM AREA CANNOT BE ACHIEVED. THIS IS DUE TO THE FACT THAT THE DESIGN PAR-TICLE INDUCED BY SO LARGE A  $P_0$  EXCEEDS THE LIMITATIONS OF THE THIRD INEQUALITY CONSTRAINT OF NYSMITH.

BM13-9/1

**SAIC**<sup>®</sup>

# INCREASE IN $P_0$ PRODUCES DRAMATIC WEIGHT INCREASE: BASELINE MISSION NOT REALIZED



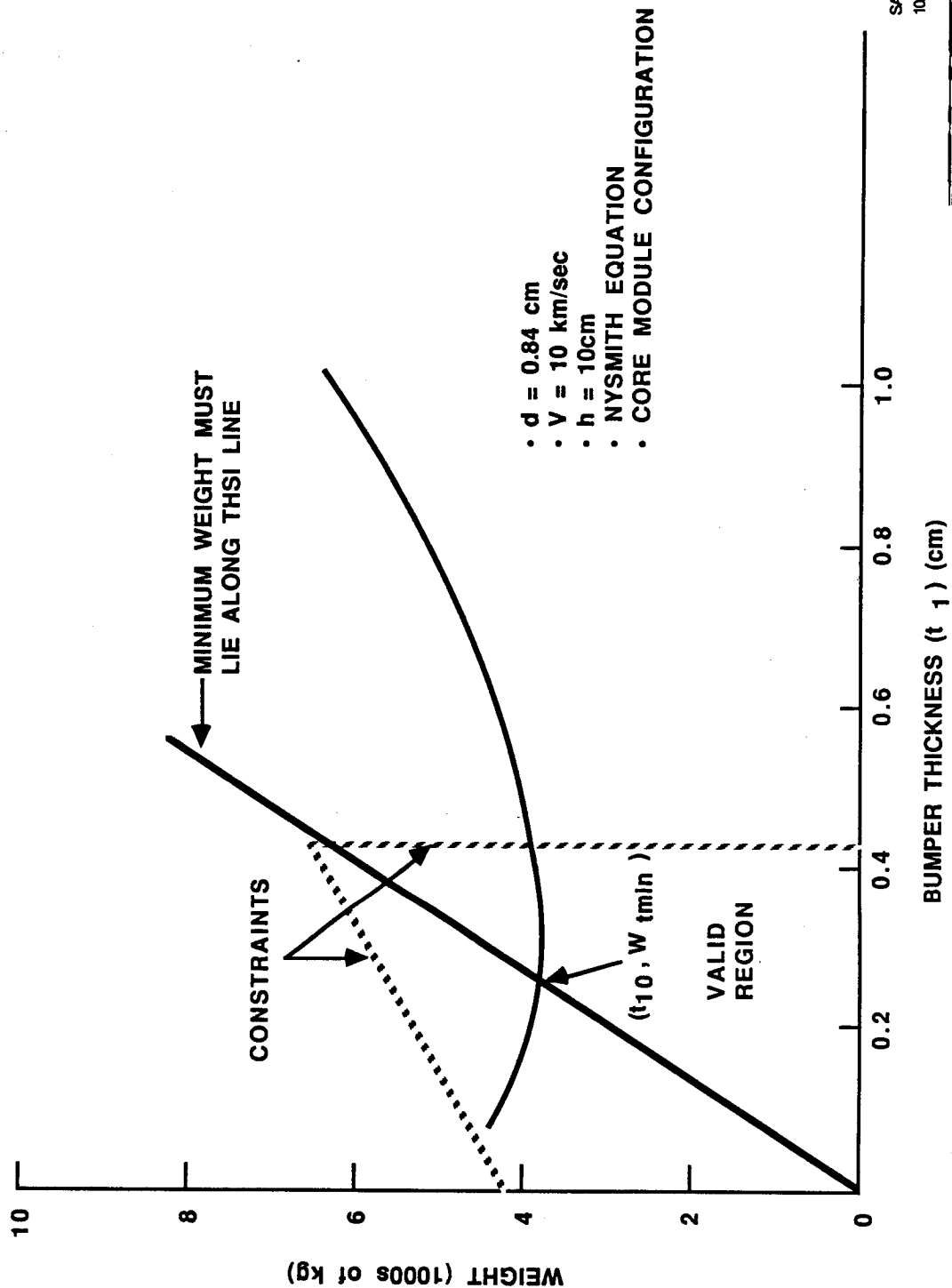
## **GP METHOD CONFIRMS THE MINIMUM WEIGHT**

**SHOWN IS THE BASIC OPTIMIZATION PROBLEM SOLVED USING GEOMETRIC PROGRAMMING (GP). THE INTERSECTION OF THE SOLID LINE AND CURVE OCCURS AT THE GLOBAL MINIMUM, VERIFYING THE GP METHODOLOGY.**

BM32-9/1



# GP METHOD CONFIRMS THE MINIMUM WEIGHT



SAC-745  
101287



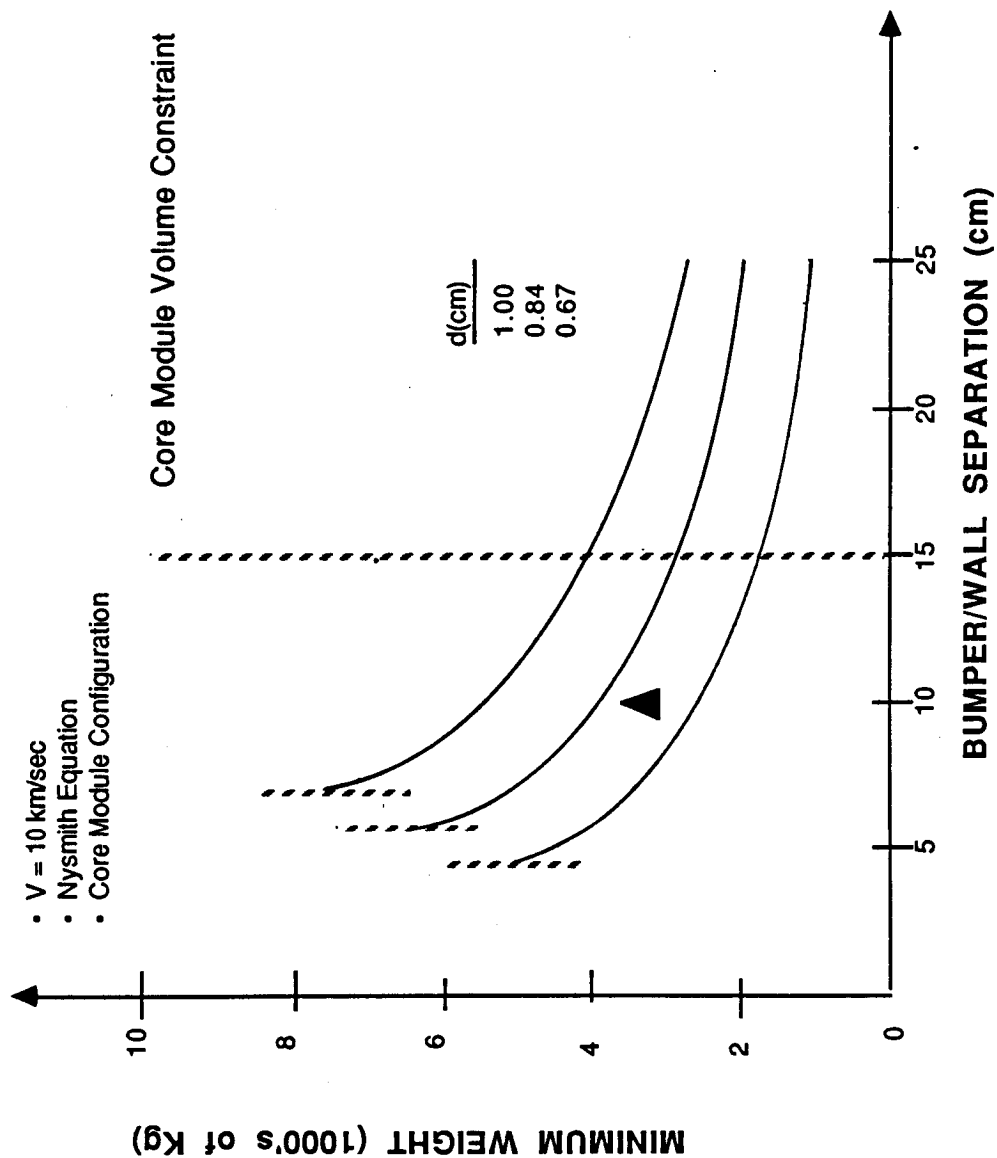
## OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

THIS SET OF CURVES SHOWS THE EFFECT OF BUMPER/WALL SEPARATION ON OPTIMAL DESIGN FOR THE NYSMITH PREDICTOR. NOTE THE HIGH PAYOFF FOR INCREASING THIS SEPARATION UP TO ABOUT 15CM, WHICH, INCIDENTALLY, CORRESPONDS TO THE CORE MODULE VOLUME CONSTRAINT FOR SHUTTLE PAYLOADS. FINALLY, TOWARDS THE LEFT OF THE THREE CURVES LIE THE CONSTRAINTS IMPOSED ON THIS SEPARATION BY THE THIRD INEQUALITY CONSTRAINT OF THE NYSMITH EQUATION. NOTE THAT THESE POINTS LIE ON A STRAIGHT LINE THROUGH THE ORIGIN.

BM33-9/1

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# OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION



## **GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN**

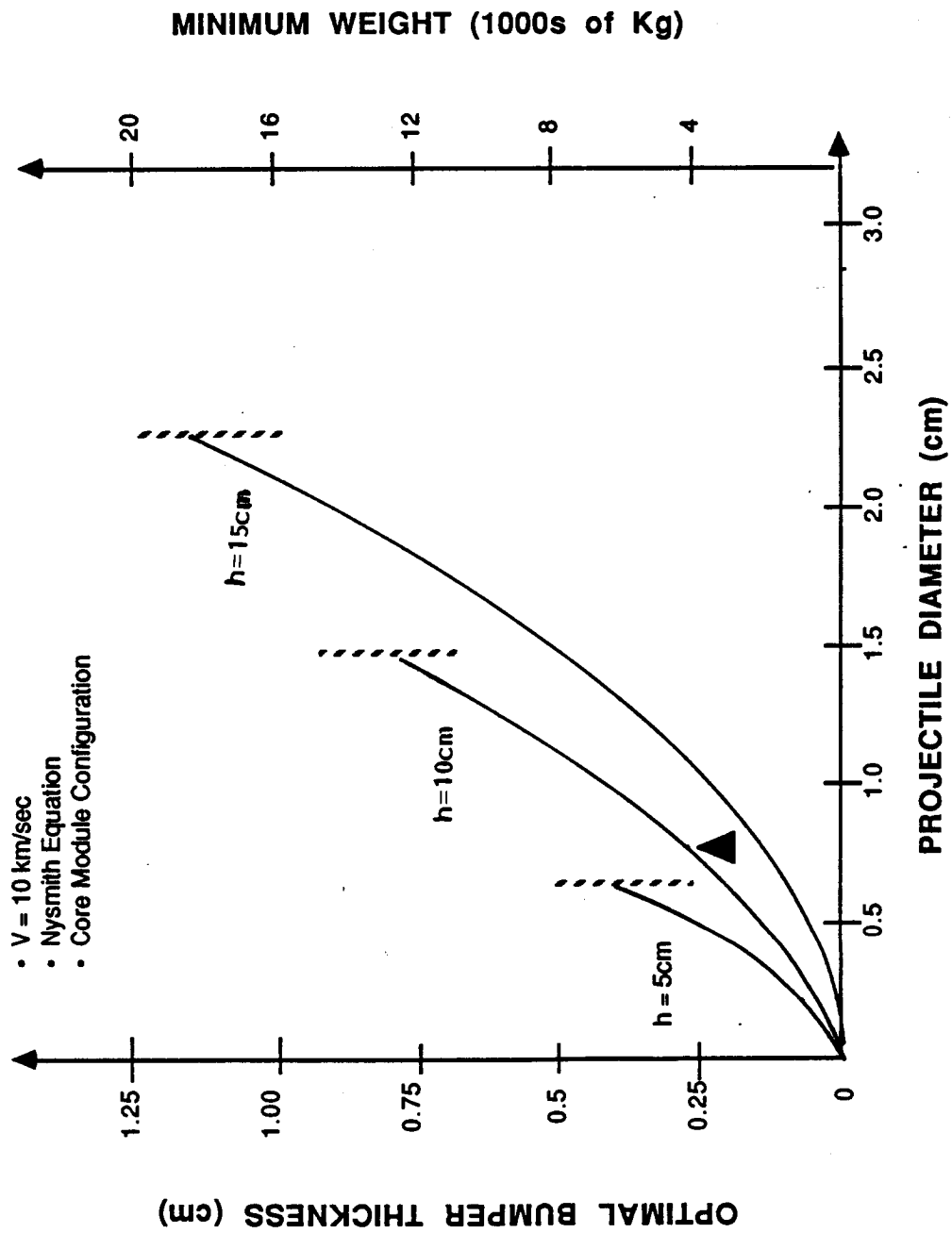
**THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER THICKNESS IS SHOWN. A 20% INCREASE IN DIAMETER ABOVE THE BASELINE REQUIRES A 40% INCREASE IN OPTIMAL BUMPER THICKNESS.**

BM34-9/1

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# GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN



**SAIC**

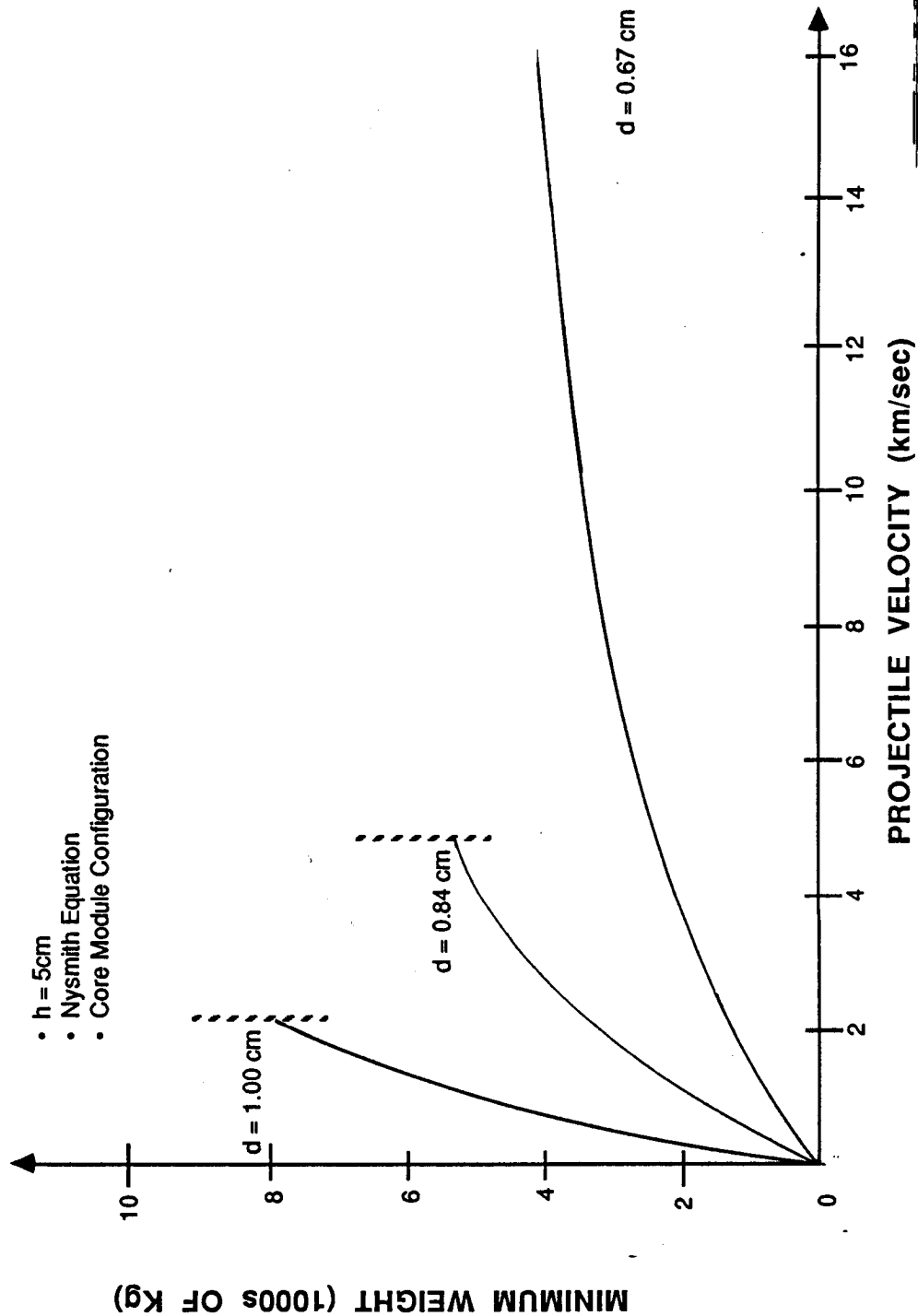
## **OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS**

THE NEXT THREE TRADE SETS SHOW THE EFFECT OF PROJECTILE VELOCITY ON DESIGN FOR VARIOUS PROJECTILE DIAMETERS, FOR 5, 10, AND 15 CM BUMPER/WALL SEPARATIONS. IN THE HIGHER VELOCITY (5-16 KM/SEC) PORTIONS OF THESE CURVES, THE DESIGN REMAINS RELATIVELY INSENSITIVE TO PROJECTILE VELOCITY.

BM24-9/1

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# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

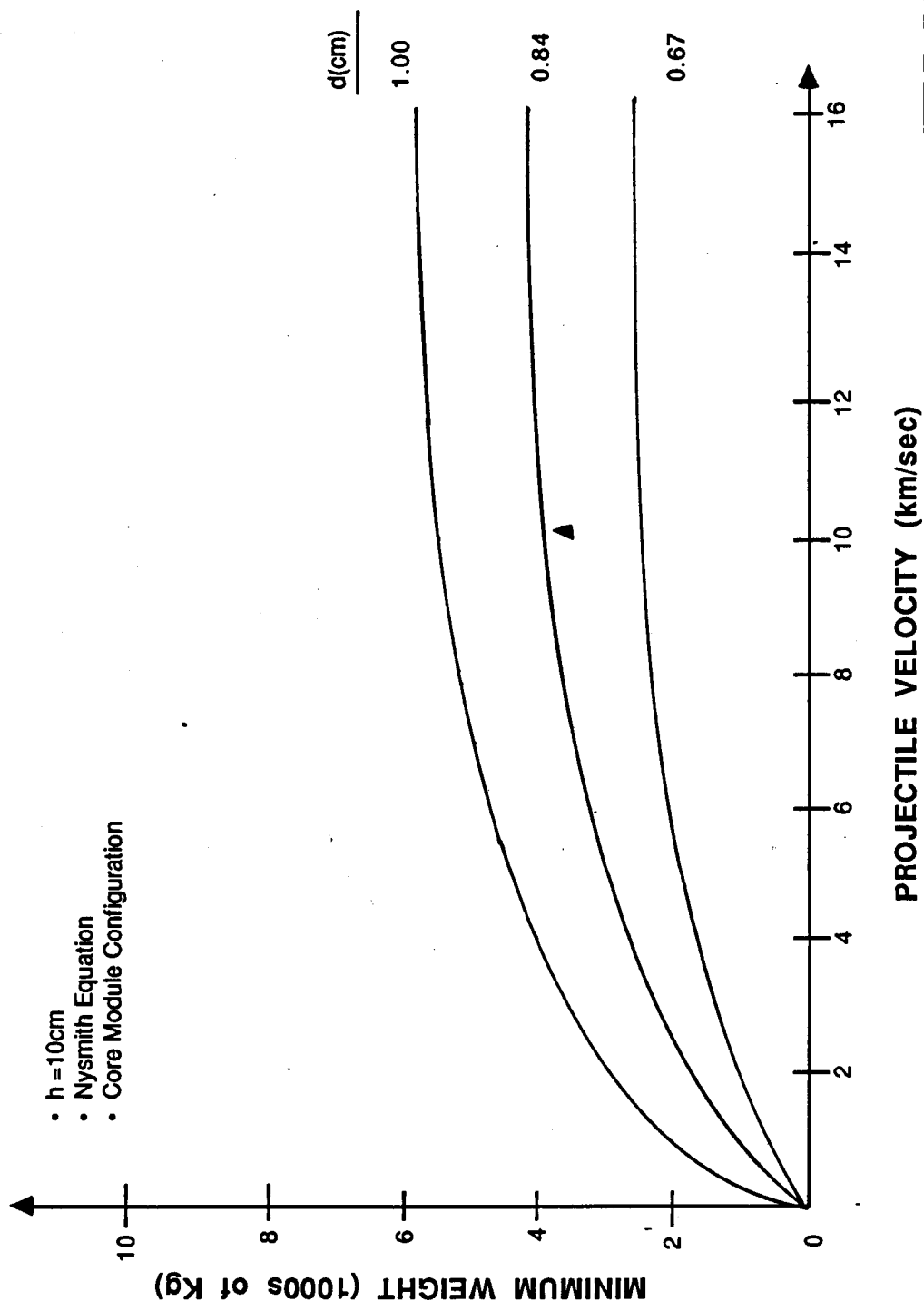


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**OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE  
VELOCITY IN HIGH VELOCITY REGIONS**



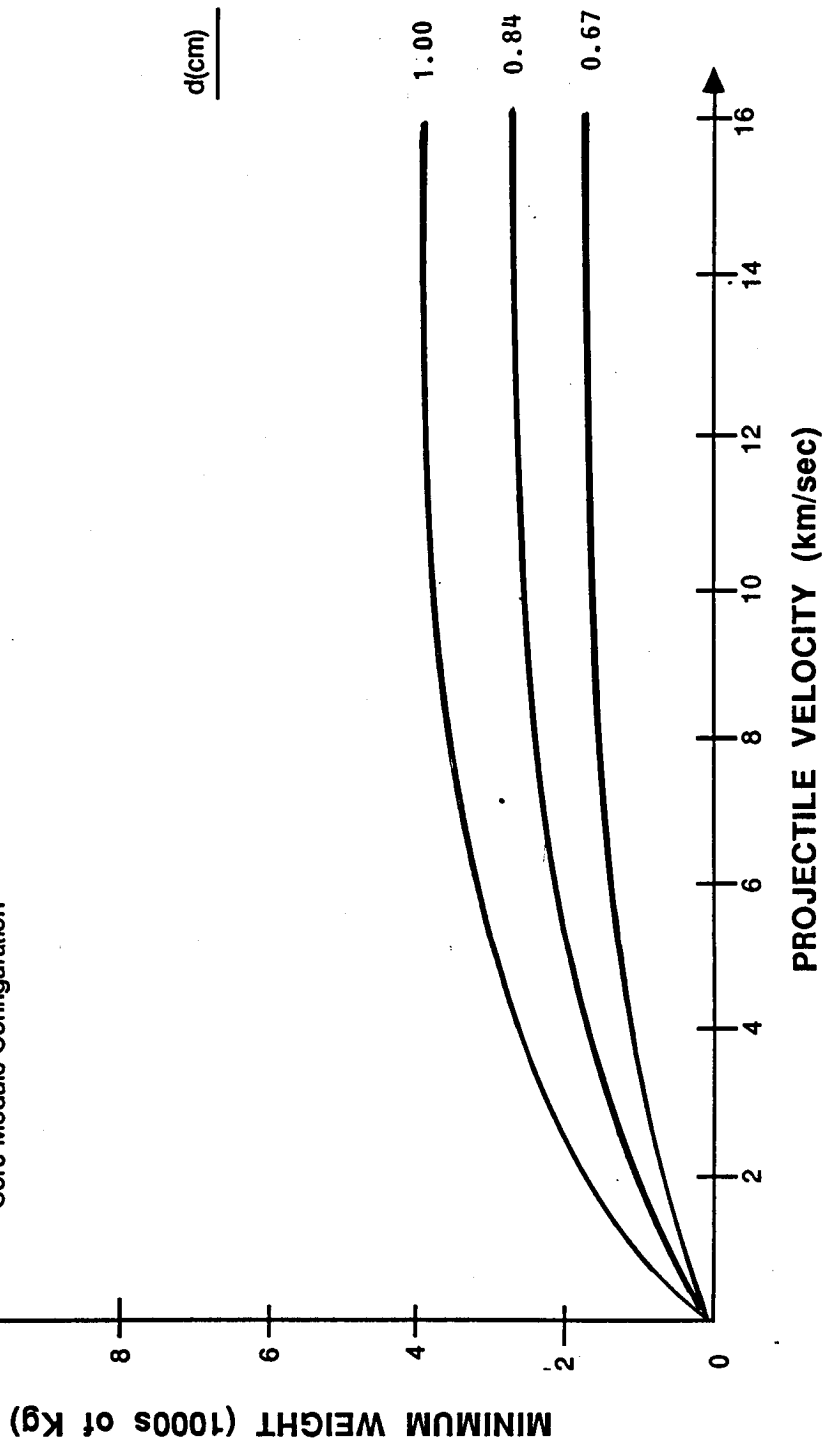
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# OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

- $h = 15\text{cm}$
- Nysmith Equation
- Core Module Configuration



**SAIL**

**OPTIMAL DESIGN IS SENSITIVE TO MISSION  
RISK FOR  $P_0$  ABOVE 0.97**

THE EFFECT OF DESIGN ON ACCEPTABLE MISSION RISK FOR VARIOUS SPACECRAFT DEBRIS AREAS, AND FOR VARIOUS BUMPER/WALL SEPARATIONS IS SHOWN IN THE NEXT THREE CHARTS. MISSION RISK PLAYS A VERY IMPORTANT ROLE IN DETERMINING THE OPTIMAL DESIGN.

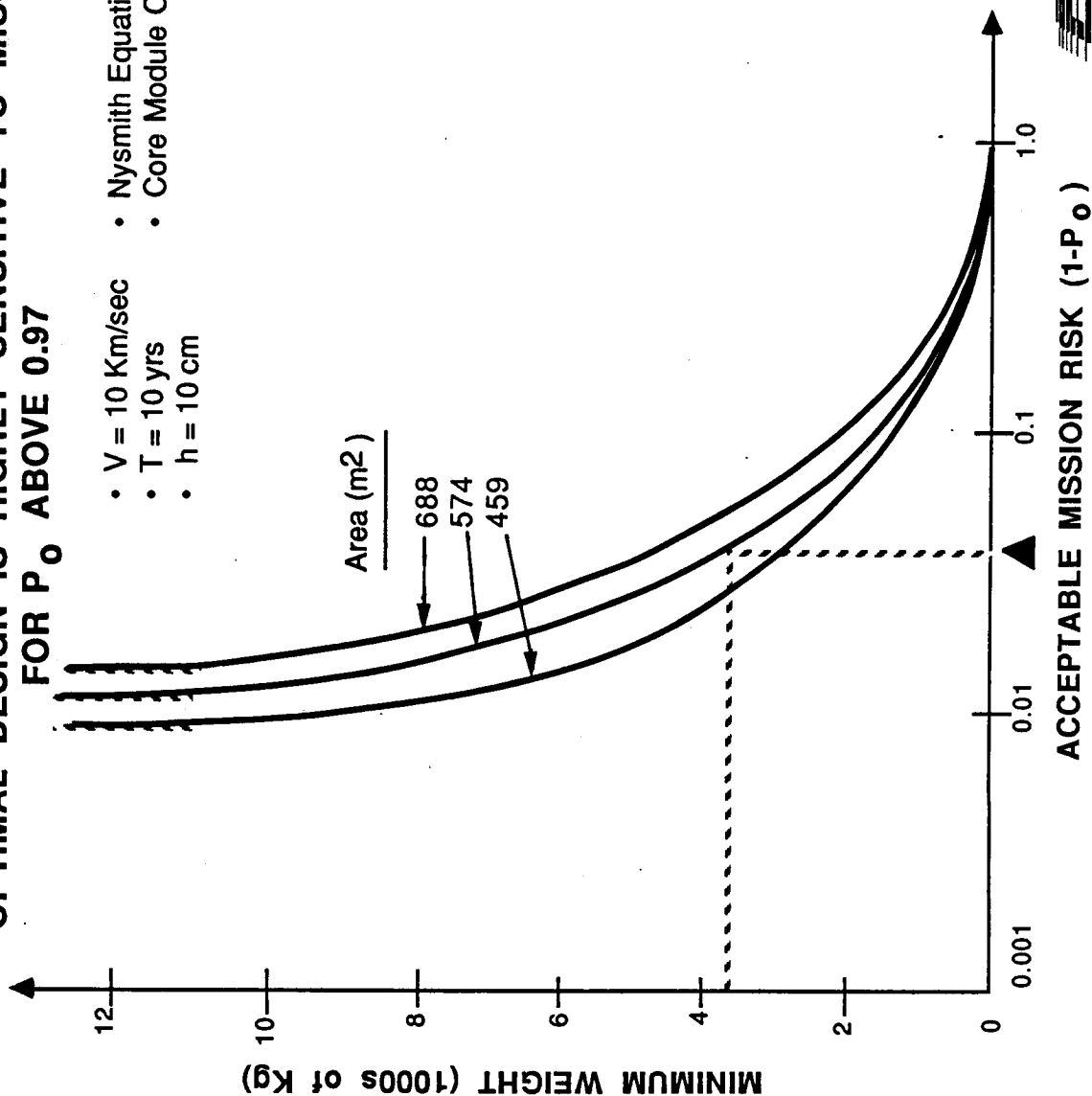
BM36-9/1

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# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_0$ ABOVE 0.97

- $V = 10 \text{ Km/sec}$
- $T = 10 \text{ yrs}$
- $h = 10 \text{ cm}$
- Nysmith Equation
- Core Module Configuration



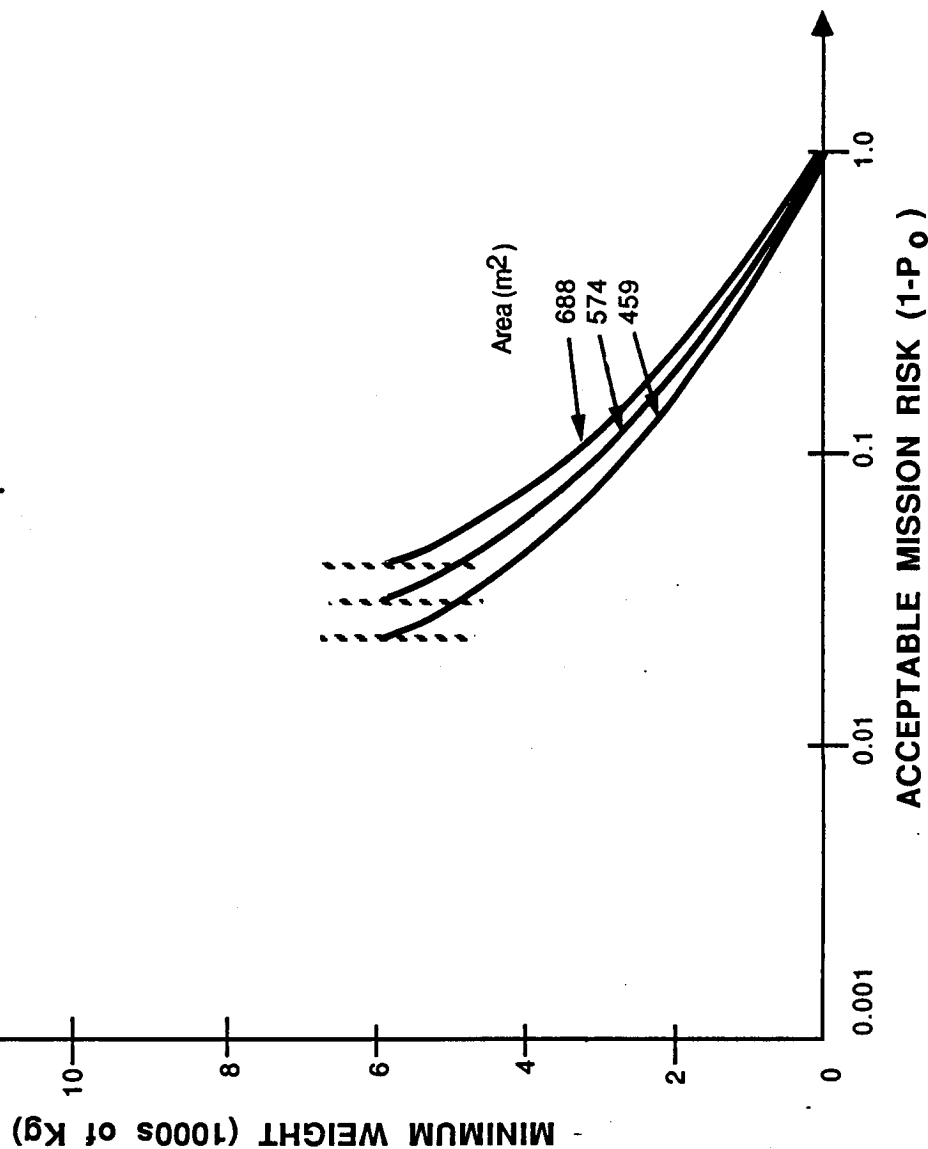
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**SAIC**<sup>TM</sup>

# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_0$ ABOVE 0.97

- $V = 10 \text{ Km/sec}$
- $T = 10 \text{ yrs}$
- $h = 5 \text{ cm}$
- Nysmith Equation
- Core Module Configuration

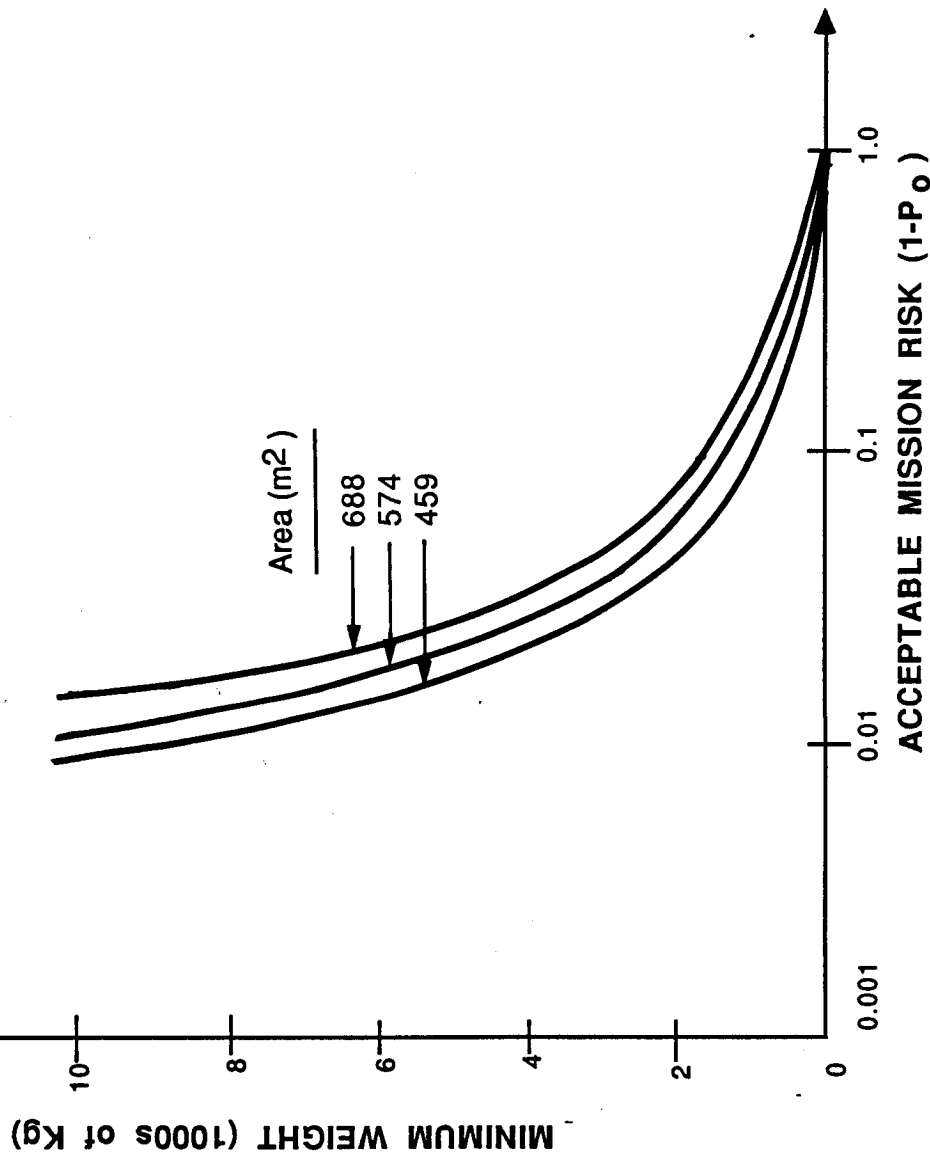


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# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR $P_0$ ABOVE 0.97

- $V = 10$  Km/sec
- $T = 10$  yrs
- $h = 15$  cm
- Nysmith Equation
- Core Module Configuration



**SAIL**

## OPTIMAL DESIGN IS SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

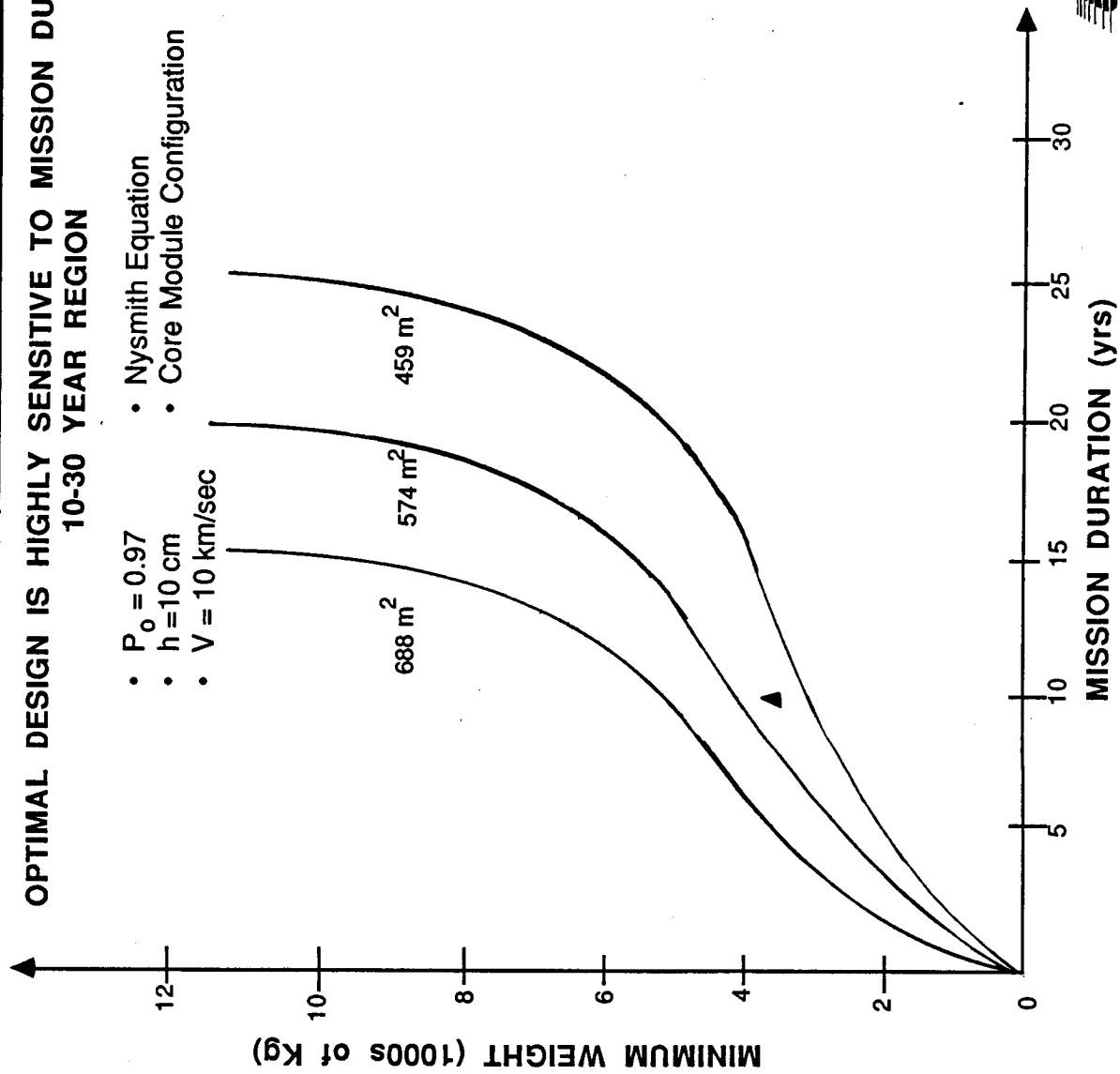
THE NEXT TWO SETS OF TRADES SHOW, FOR DIFFERENT  $P_{Os}$ , THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR VARIOUS SPACECRAFT DEBRIS AREAS. NOTE THE HIGH SENSITIVITY, EVEN INFLECTION IN SOME CASES, OCCURRING IN THE 10-30 YEAR RANGE.

BM37-9/1

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# OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

- $P_o = 0.97$
- Nysmith Equation
- $h = 10 \text{ cm}$
- Core Module Configuration
- $V = 10 \text{ km/sec}$



**SAIL.**

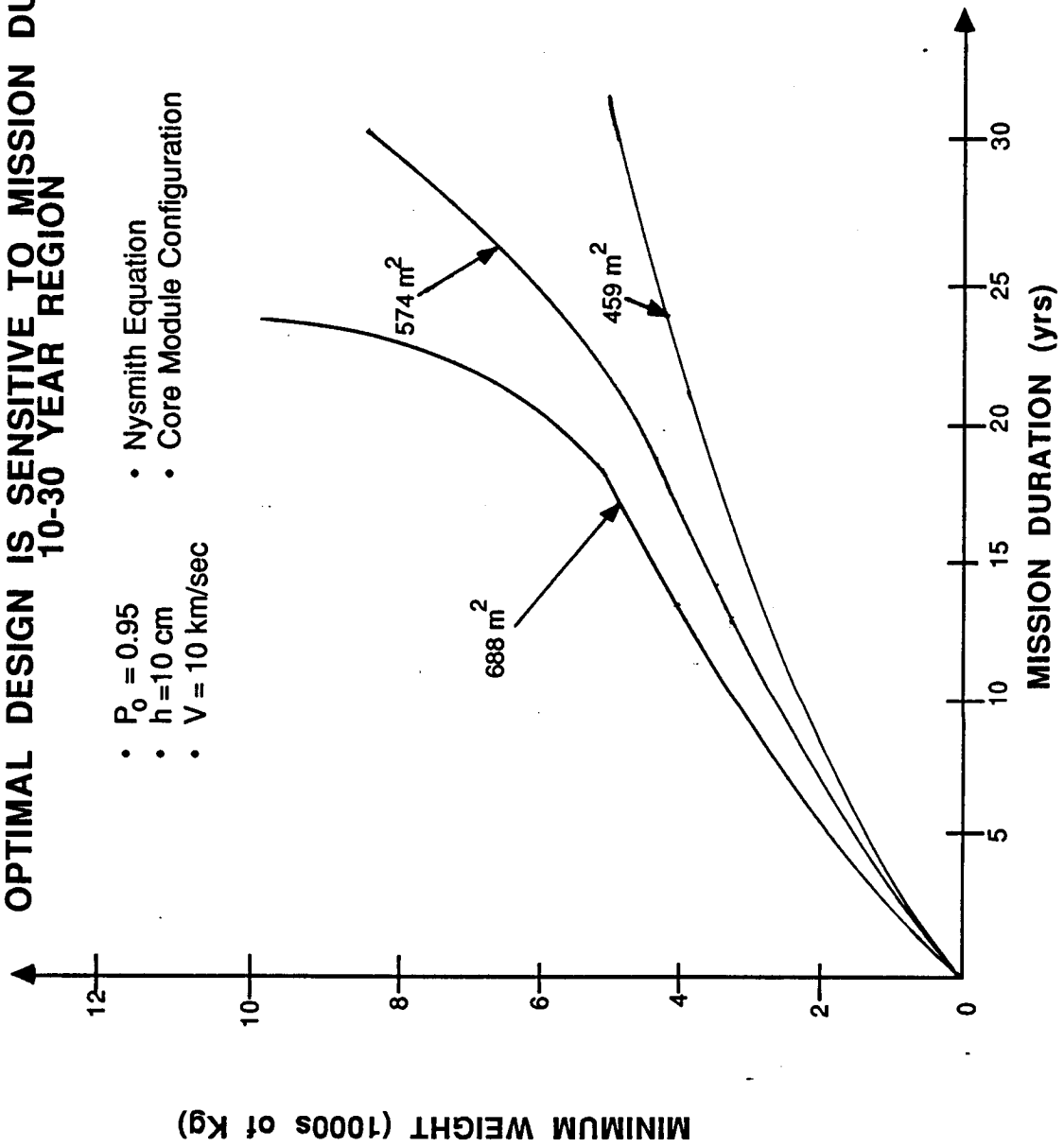
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# OPTIMAL DESIGN IS SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

- $P_0 = 0.95$
- Nysmith Equation
- $h = 10 \text{ cm}$
- Core Module Configuration
- $V = 10 \text{ km/sec}$



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# SECTION IV

GEOMETRIC PROGRAMMING APPLIED TO  
THE BOEING SUBPREDICTORS.

BM29-8/21

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## WHAT YOU WILL SEE IN SECTION IV

- DEFINITIONS AND BASELINE DESIGN PARAMETERS FOR THE THREE BOEING SUBPREDICTORS
- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE BOEING SUBPREDICTORS
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
  - PROJECTILE VELOCITY
  - BUMPER/WALL SEPARATION
  - PROJECTILE DIAMETER
  - MISSION RISK
  - MISSION DURATION
- THE OPTIMAL RATIO FOR BUMPER AND WALL AS A FUNCTION OF PROJECTILE DIAMETER

BM4 10/13

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## THE PEN4 PREDICTOR

THE PEN4 PREDICTOR WITH PARAMETER DEFINITION IS SHOWN FOR REFERENCE. NOTE THAT THERE IS NO DEPENDENCE ON BUMPER/WALL SEPARATION. ALSO, NOTE THAT THE PEN4 PREDICTOR IS VELOCITY CONSTRAINED. THIS PREDICTOR WAS OPTIMIZED USING A SEARCH TECHNIQUE, WITH THE VELOCITY CONSTRAINT CHECKED EXTERNALLY TO THE OPTIMIZATION.

BM15-8/21



## THE PEN4 PREDICTOR

$$t_2 = 1.67 \left( \frac{C_1 \rho_p}{2 S y_2} \right)^{.31} \left( \frac{.281 D \rho_p}{\rho_2} \right)^{1/3} \cos(\theta)$$

$$C_1 = \frac{a-b}{c+d}$$

$$a = 1.33 V^2 R p^2 \rho_p$$

$$b = 8 S y_1 t_1 e^{-3.125 \times 10^{-4} V / \cos(\theta)}$$

$$c = 1.33 R p^2 \rho_p$$

$$d = R p t_1 \rho_1 / \cos(\theta)$$

Valid for  $V \leq V_f + 4000$ , where

$$V_f = \begin{cases} 4100, & \text{if } t_1 / D \leq 0.4 \\ 4986 (t_1 / D)^{0.21}, & \text{if } t_1 / D > 0.4 \end{cases}$$

BMO1-8/21

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## THE PEN4 PREDICTOR (CONTINUED)

$V$	= particle velocity, ft/sec
$t_1$	= bumper thickness, ft
$t_2$	= wall thickness, ft
$D$	= particle diameter, ft
$R_p$	= particle radius, ft
$\rho_p$	= projectile density, slugs/ft <sup>3</sup>
$\rho_1$	= bumper density, slugs/ft <sup>3</sup>
$\rho_2$	= wall density, slugs/ft <sup>3</sup>
$\theta$	= impact angle from the normal, degrees
$Sy_1$	= bumper yield strength, lb/ft <sup>2</sup>
$Sy_2$	= wall yield strength, lb/ft <sup>2</sup>

No bumper/wall separation dependency

## **BASELINE DESIGN PARAMETERS**

**THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE PEN4 PREDICTOR ARE SHOWN. SINCE THIS PREDICTOR IS NOT VALID FOR A PROJECTILE VELOCITY OF 10 KM/SEC, NO OPTIMAL DESIGN IS INDUCED.**

BM02-9/9

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# BASELINE DESIGN PARAMETERS

## DESIGN ASSUMPTIONS

$P_o = 0.97$	(PROBABILITY OF NO PENETRATION)
$T = 10 \text{ yrs}$	(MISSION DURATION)
$A_d = 574 \text{ m}^2$	(DEBRIS AREA)
$A_m = 403 \text{ m}^2$	(METEOROID AREA)
$Alt = 500 \text{ km}$	(AVERAGE ALTITUDE)
$V_m = 20 \text{ km/sec}$	(AVERAGE METEOROID VELOCITY)
$V_D = 10 \text{ km/sec}$	(AVERAGE DEBRIS VELOCITY)
$\rho_m = 0.5 \text{ gm/cm}^3$	(METEOROID DENSITY)
$\rho_D = 2.81 \text{ gm/cm}^3$	(DEBRIS DENSITY)
$\rho_1 = 2.81 \text{ gm/cm}^3$	
$\rho_2 = 2.81 \text{ gm/cm}^3$	
$\theta = 0 \text{ degrees}$	
$Sy_1 = 7344000 \text{ lb/ft}^2 \text{ (51 Ksi)}$	
$Sy_2 = Sy_1$	

OPTIMAL DESIGN  
(BALLISTIC LIMIT)

INVALID

BM03-8/21

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## **THE BURCH PREDICTOR (NORMAL IMPACT)**

**THE BURCH PREDICTOR FOR NORMAL IMPACTS IS SHOWN WITH PARAMETER DEFINITION. NOTE THAT THERE IS NO DEPENDENCE ON PROJECTILE OR WALL MATERIAL PROPERTIES.**

BM16-8/21

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# THE BURCH PREDICTOR (NORMAL IMPACT)

$$t_2 = \left( \frac{F_1 D}{N} \right)^{1.71} \left( \frac{C}{V} \right)^{2.29} / S^{0.71}, \text{ where}$$

$$F_1 = 2.42 (t_1 / D)^{-0.33} + 4.26 (t_1 / D)^{0.33} - 4.18$$

C = speed of sound in shield, ft/sec =  $\sqrt{E_1 / \rho_1}$

E<sub>1</sub> = Youngs Modulus of Elasticity for bumper, lb/ft-sec<sup>2</sup>

ρ<sub>1</sub> = bumper density, lb/ft<sup>3</sup>

V = projectile velocity, ft/sec

S = spacing, inches

D = projectile diameter, inches

t<sub>1</sub> = bumper thickness, inches

t<sub>2</sub> = wall thickness, inches

N = number of plates to penetrate after 1st bumper

No projectile material property dependency

No wall material property dependency

## THE MODIFIED BURCH PREDICTOR

THE MODIFIED BURCH PREDICTOR IS SHOWN FOR REFERENCE. NOTE THAT THIS PREDICTOR IS A POSYNOMIAL, WHICH ALLOWS IT TO BE OPTIMIZED GLOBALLY USING GEOMETRIC PROGRAMMING.

BM17-8/21

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# THE MODIFIED BURCH PREDICTOR

SAME AS THE BURCH PREDICTOR EXCEPT:

$$F_1 = 2.8 (t_1 / D)^{0.57} + 1.58 (t_1 / D)^{-0.57}$$

BM10-8/21

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## MODIFIED BURCH PREDICTOR INDUCES SMALL ERRORS

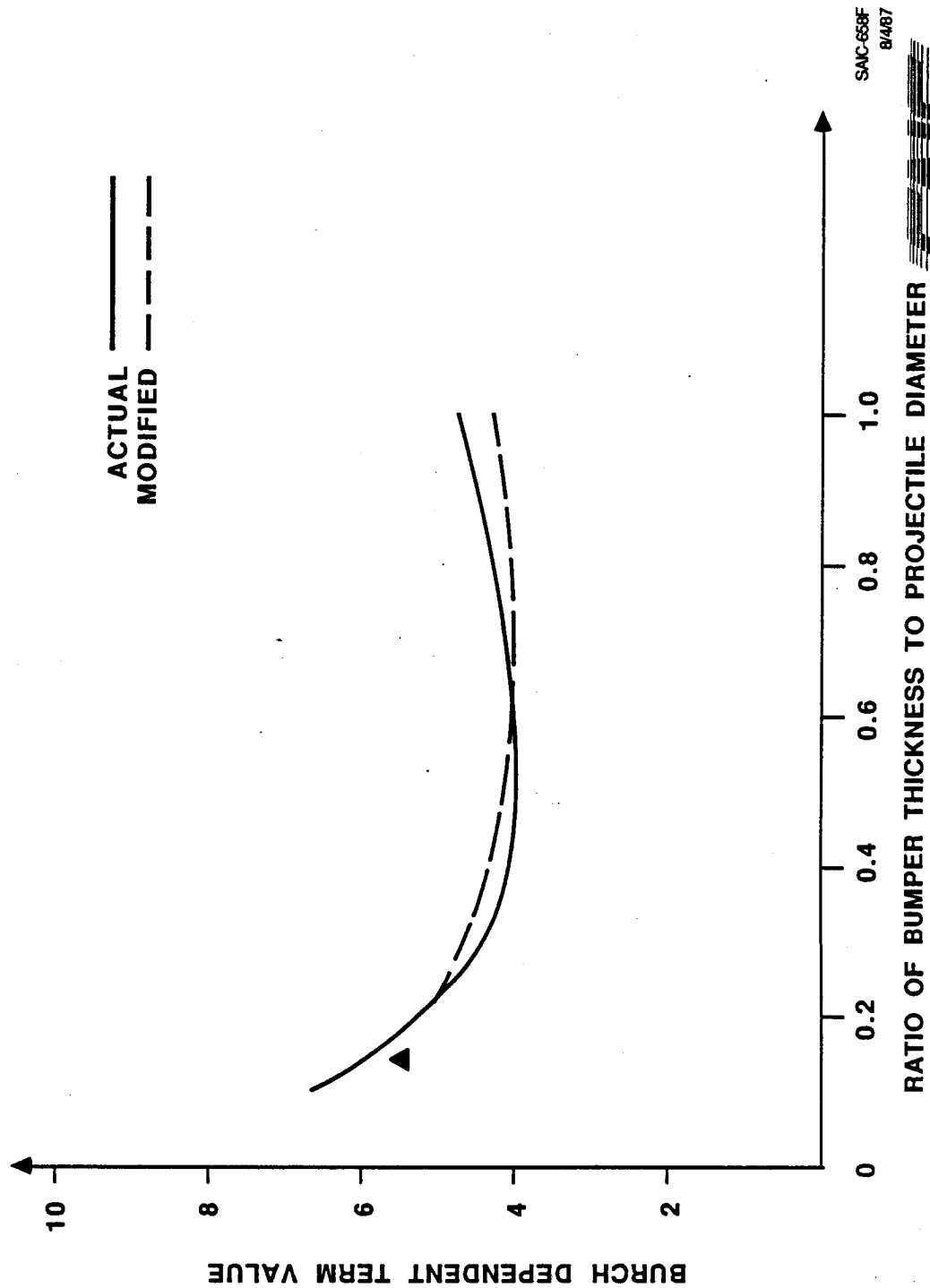
SHOWN IS THE BURCH DEPENDENT TERM VALUE (PROPORTIONAL TO THE WALL THICKNESS) AS A FUNCTION OF THE RATIO OF THE BUMPER THICKNESS TO PROJECTILE DIAMETER FOR THE BURCH AND MODIFIED BURCH PREDICTORS. USING THE MODIFIED BURCH PREDICTOR ALLOWS THE DESIGNER TO APPLY THE GEOMETRIC PROGRAMMING OPTIMIZATION TECHNIQUE, THUS REDUCING COMPUTER USAGE AND GUARANTEEING GLOBAL DESIGN OPTIMIZATION, ALL FOR A SMALL PRICE IN TERMS OF DESIGN ERROR.

BM01-8/5

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# MODIFIED BURCH PREDICTOR INDUCES SMALL ERRORS



SAC-658F  
8/487



RATIO OF BUMPER THICKNESS TO PROJECTILE DIAMETER

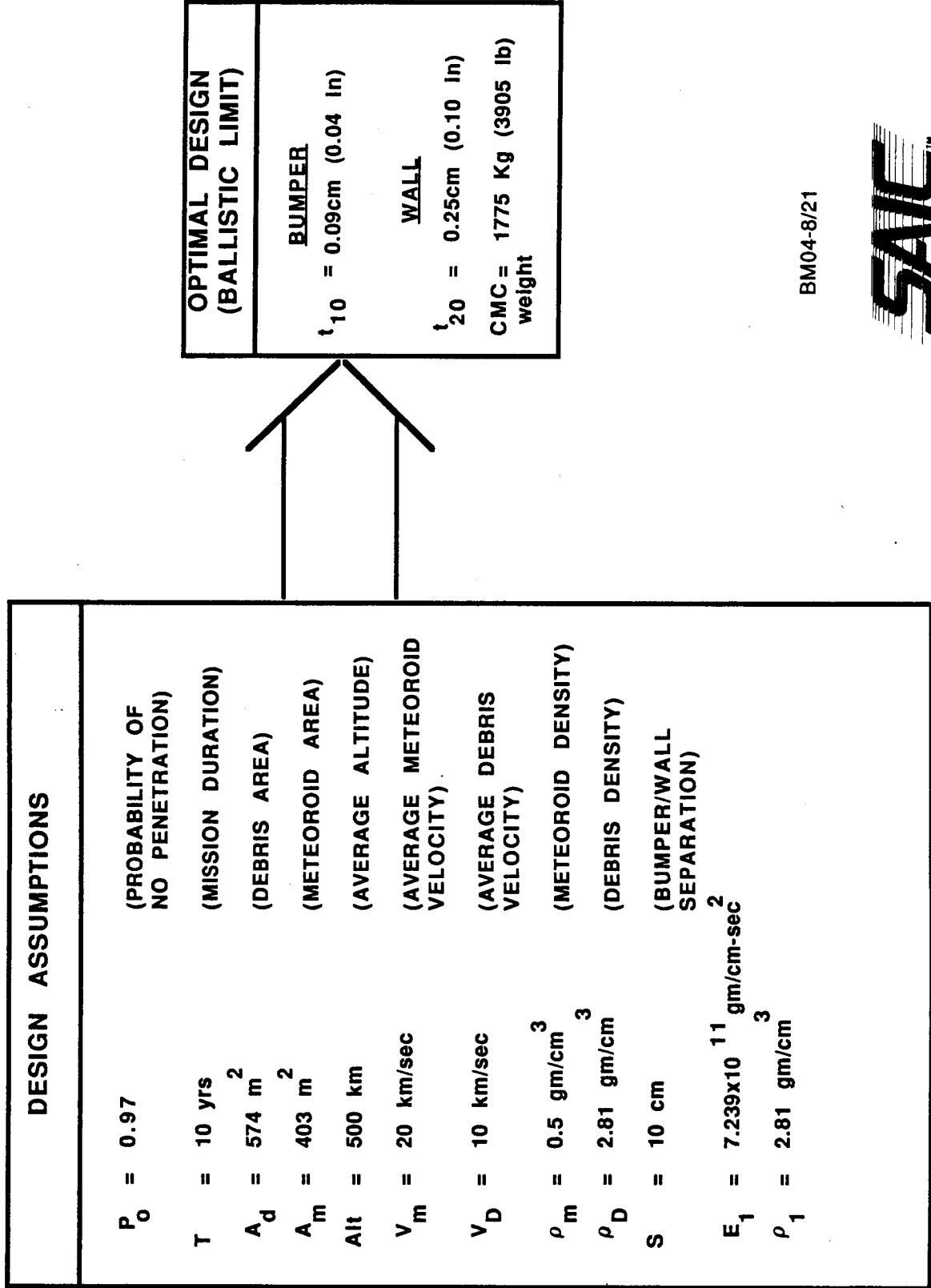
## **BASELINE DESIGN PARAMETERS**

**THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE MODIFIED BURCH PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRIBUTION IS 26% BUMPER, 74% WALL.**

**BM03A-9/9**



# BASELINE DESIGN PARAMETERS



BM04-8/21



## THE WILKINSON PREDICTOR

THE WILKINSON PREDICTOR WITH PARAMETER DEFINITION IS SHOWN FOR REFERENCE. NOTE THAT THIS PREDICTOR FORMS A COMPLETE SET OF PARAMETERS. ALSO, NOTE THAT THE WILKINSON PREDICTOR IS A PIECEWISE CONTINUOUS MODEL. THE WILKINSON PREDICTOR WAS OPTIMIZED USING GEOMETRIC PROGRAMMING.

BM18-8/21

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## THE WILKINSON PREDICTOR

$$t_2 = 0.364 D^4 \rho_p^2 V_n / (L_2 S^2 \rho_1 t_1 \rho_2), \text{ if } \frac{D \rho_p}{\rho_1 t_1} > 1.$$

$$t_2 = 0.364 D^3 \rho_p V_n / (L_2 S^2 \rho_2), \text{ if } \frac{D \rho_p}{\rho_1 t_1} \leq 1.$$

$\rho_p$  = projectile density, gm/cm<sup>3</sup>

$D$  = projectile diameter, cm

$V_n$  = normal component of velocity vector, km/sec

$S$  = spacing, cm

$\rho_1$  = bumper density, gm/cm<sup>3</sup>

$\rho_2$  = wall density, gm/cm<sup>3</sup>

$L_2$  = wall material constant

$t_1$  = bumper thickness, cm

$t_2$  = wall thickness, cm

BM11-8/21

**SAIL**<sup>™</sup>

## **BASELINE DESIGN PARAMETERS**

**THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE WILKINSON  
PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRI-  
BUTION IS 50% WALL, 50% BUMPER.**

BM01-9/9

**SAIC**<sup>™</sup>

# BASELINE DESIGN PARAMETERS

DESIGN ASSUMPTIONS	
$P_o = 0.97$	(PROBABILITY OF NO PENETRATION)
$T = 10 \text{ yrs}$	(MISSION DURATION)
$A_d = 574 \text{ m}^2$	(DEBRIS AREA)
$A_m = 403 \text{ m}^2$	(METEOROID AREA)
$Alt = 500 \text{ km}$	(AVERAGE ALTITUDE)
$V_m = 20 \text{ km/sec}$	(AVERAGE METEOROID VELOCITY)
$V_D = 10 \text{ km/sec}$	(AVERAGE DEBRIS VELOCITY)
$\rho_m = 0.5 \text{ gm/cm}^3$	(METEOROID DENSITY)
$\rho_D = 2.81 \text{ gm/cm}^3$	(DEBRIS DENSITY)
$S = 10 \text{ cm}$	(BUMPER/WALL SEPARATION)
$\rho_1 = 2.81 \text{ gm/cm}^3$	
$\rho_2 = \rho_1$	
$L_2 = 0.401$	

OPTIMAL DESIGN (BALLISTIC LIMIT)	
<u>BUMPER</u>	$t_{10} = 0.21 \text{ cm (0.08 in)}$
<u>WALL</u>	$t_{20} = 0.21 \text{ cm (0.08 in)}$
CMC = 2209 Kg (4860 lb) weight	

BM05-8/21



## **DEBRIS ENVIRONMENT DRIVES FOR MODIFIED BURCH**

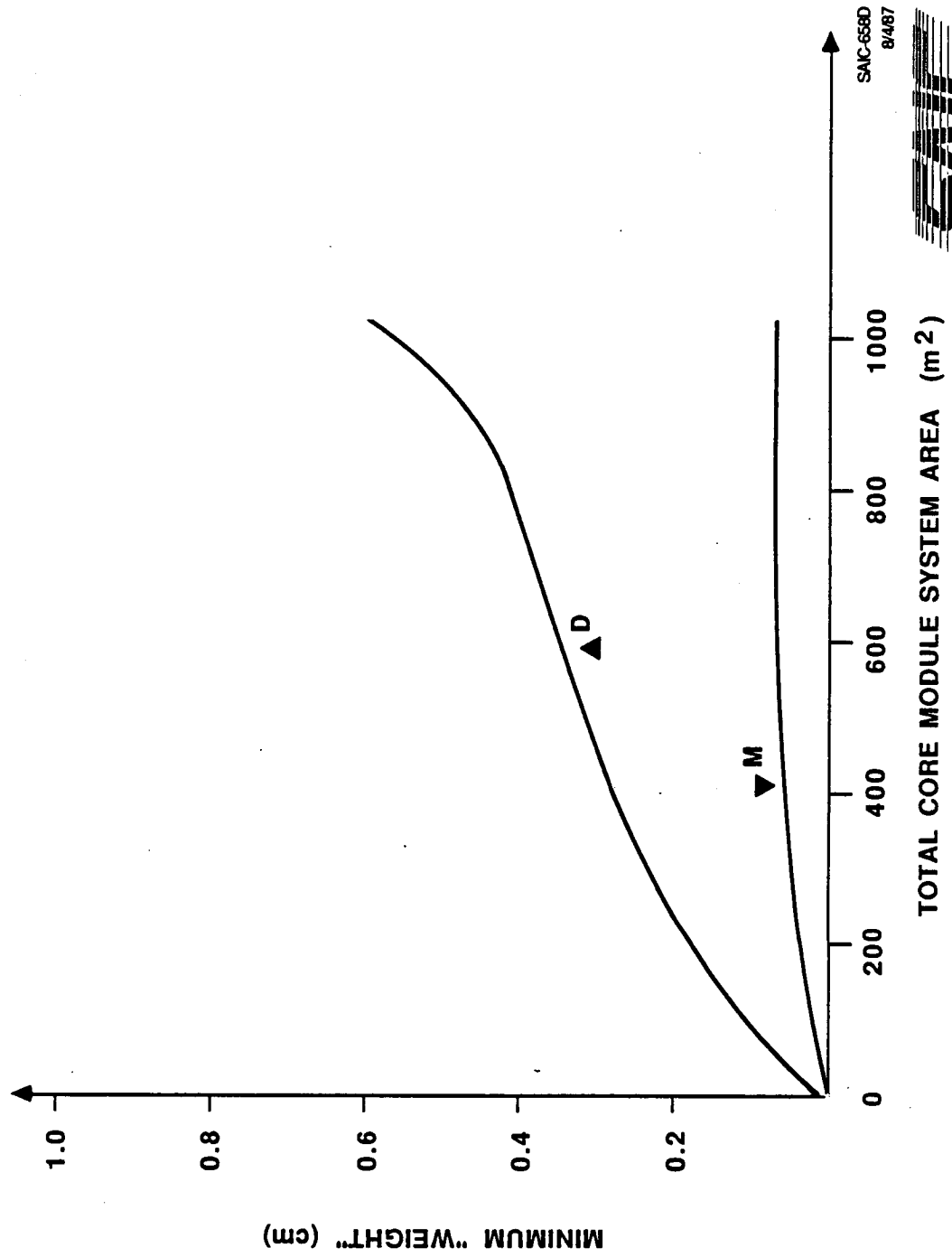
**THE EFFECT OF CHANGES IN THE CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE DEBRIS AND METEOROID CASES FOR THE MODIFIED BURCH SUBPREDICTOR IS SHOWN. AGAIN, THE DEBRIS ENVIRONMENT DOMINATES THAT OF THE METEOROID.**

BM04-8/5

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# DEBRIS ENVIRONMENT DRIVES FOR MODIFIED BURCH



SAC-6580  
8/487



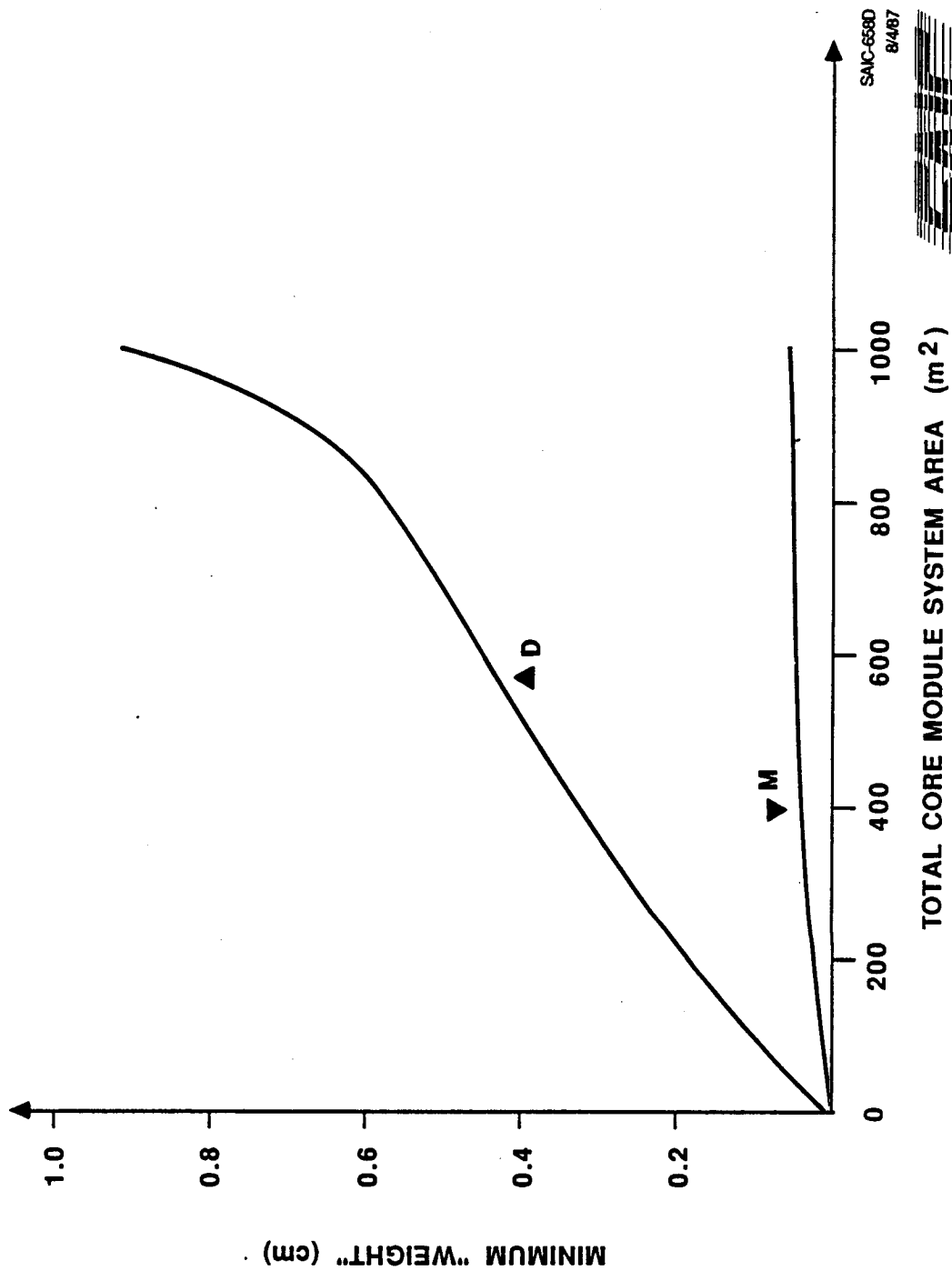
## **DEBRIS ENVIRONMENT DRIVES FOR WILKINSON**

SHOWN IS THE EFFECT OF CHANGES IN CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE WILKINSON SUBPREDICTOR. THE DOMINANCE OF THE DEBRIS SCENARIO OVER THE METEOROID SCENARIO IS MORE STRIKING FOR WILKINSON THAN NYSMITH BECAUSE THE WILKINSON PREDICTOR ACCOUNTS FOR PROJECTILE DENSITY AND THE NYSMITH DOES NOT.

BM03-8/5

**SAIC**<sup>TM</sup>

# DEBRIS ENVIRONMENT DRIVES FOR WILKINSON



SAIC

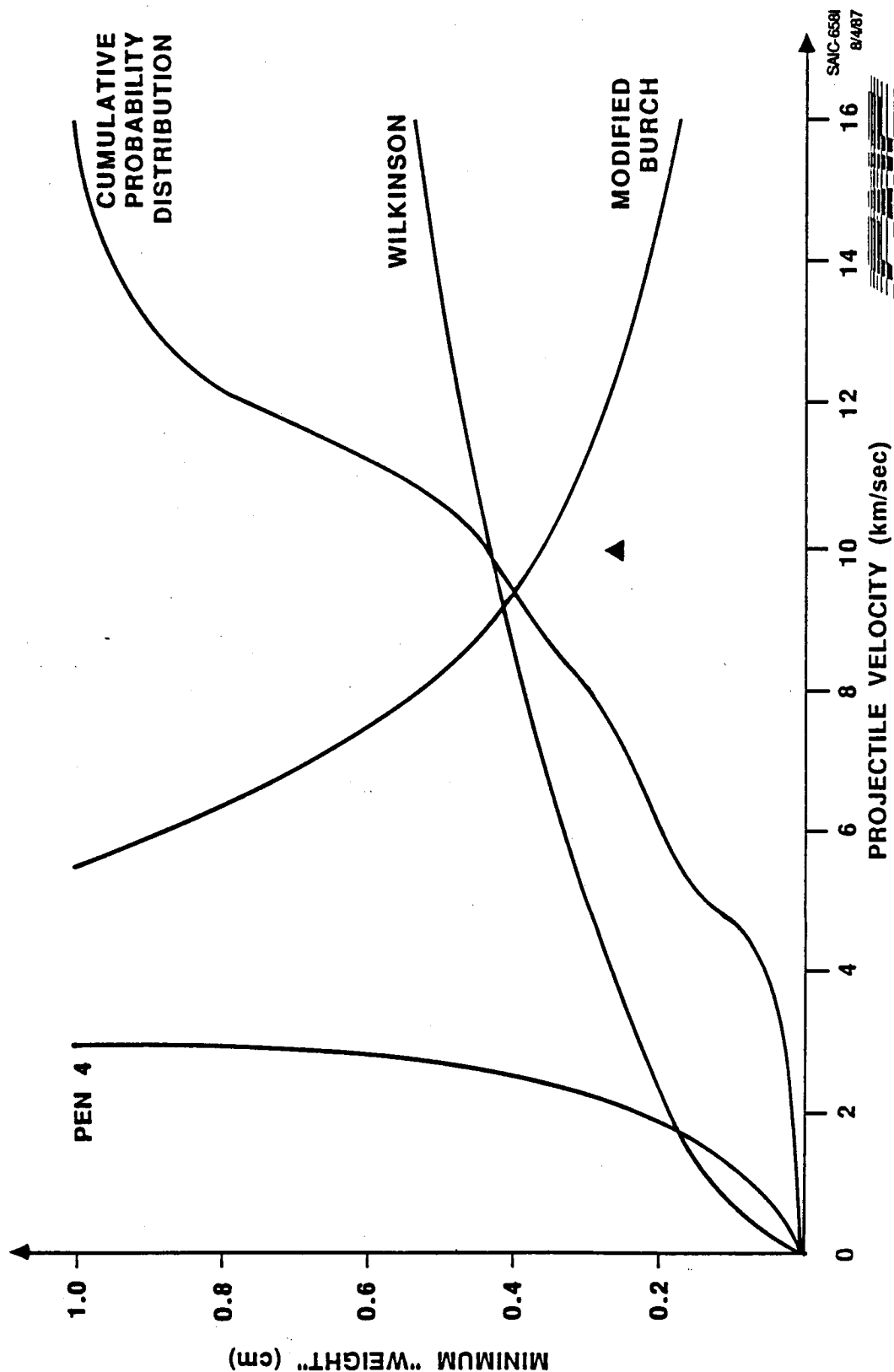
## VELOCITY SENSITIVITY FOR THE BOEING SUBPREDICTORS

THE DESIGN SENSITIVITY TO PROJECTILE VELOCITY FOR THE THREE BOEING SUBPREDICTORS IS SHOWN. BOTH THE PEN4 AND WILKINSON SUBPREDICTORS SHOW OPTIMAL DESIGN INCREASING WITH INCREASING VELOCITY, ALTHOUGH THE PEN4 CURVE IS CONVEX, WHILE THE WILKINSON CURVE IS CONCAVE. FURTHERMORE, THE PEN4 SUBPREDICTOR IS ONLY VALID UP TO ABOUT 2.85 km/sec. THE MODIFIED BURCH SUBPREDICTOR IS A DECREASING CURVE AND INTERSECTS THE WILKINSON CURVE AT ABOUT 9 km/sec. ALSO SHOWN IS THE CUMULATIVE PROBABILITY DISTRIBUTION FOR SPACE DEBRIS AT 500 km ALTITUDE AND 30° INCLINATION. NOTE THAT 80% PROBABILITY OCCURS AT ROUGHLY 12 km/sec. NOTE, ALSO, THAT VELOCITIES UP TO 10 km/sec ONLY ACCOUNT FOR ROUGHLY 40% OF THE THREAT DISTRIBUTION.

BM02-8/5

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# VELOCITY SENSITIVITY FOR THE BOEING SUBPREDICTORS



SAC-6581  
B/487



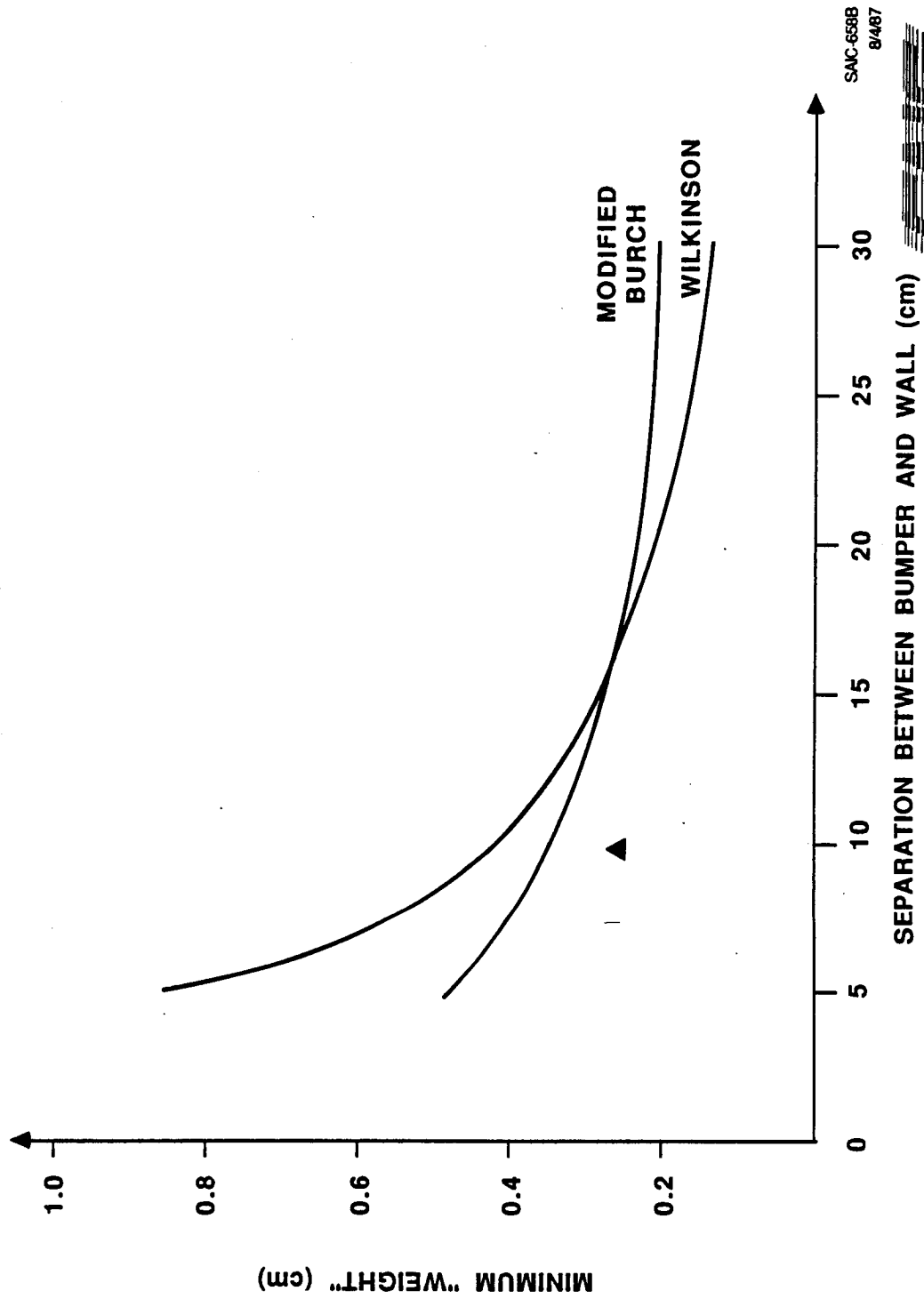
**GP SHOWS SEPARATION SENSITIVITIES  
FOR MODIFIED BURCH AND WILKINSON**

**THE DECREASE IN OPTIMAL DESIGN FOR AN INCREASE IN BUMPER/WALL  
SEPARATION FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS  
IS SHOWN. NOTE THAT THE WILKINSON CURVE IS MUCH MORE SENSITIVE  
TO INCREASES IN BUMPER/WALL SEPARATION.**

BM06-8/5

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**GP SHOWS SEPARATION SENSITIVITIES FOR  
MODIFIED BURCH AND WILKINSON**



SAC-6588  
8/487



## SENSITIVITY OF OPTIMAL DESIGN TO THREAT

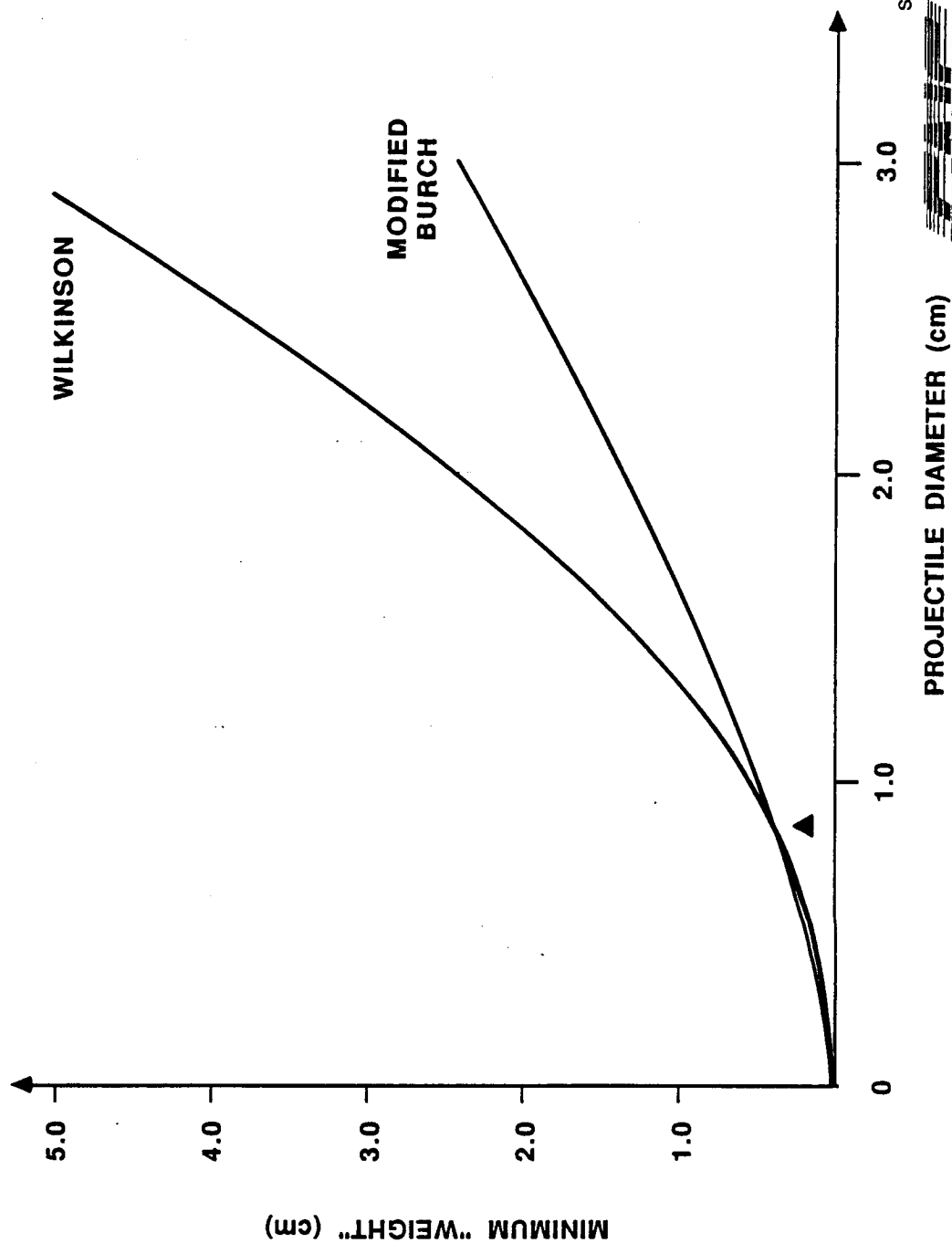
SHOWN IN THE NEXT TWO CHARTS IS THE DESIGN SENSITIVITY TO PROJECTILE DIAMETER FOR THE WILKINSON AND MODIFIED BURCH SUBPREDICTORS. NOTE THAT THE MODIFIED BURCH CURVE DOMINATES THE DESIGN UP TO ABOUT 0.52 cm PROJECTILE DIAMETER, WHERE THE WILKINSON CURVE TAKES OVER.

BM05-8/5

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# SENSITIVITY OF OPTIMAL DESIGN TO THREAT



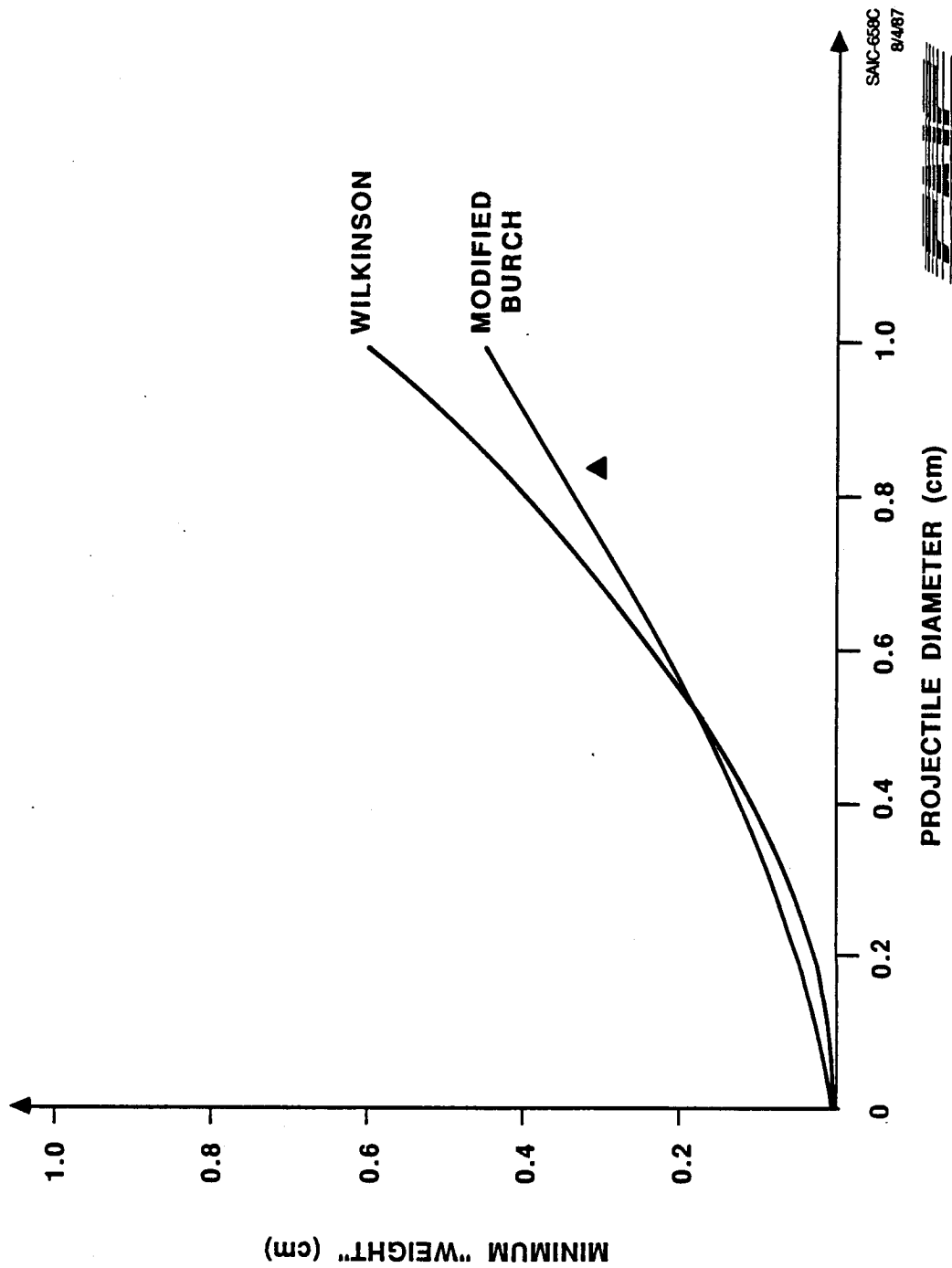
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8/487



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# SENSITIVITY OF OPTIMAL DESIGN TO THREAT



SAC-658C  
8/487

**SAIL.**

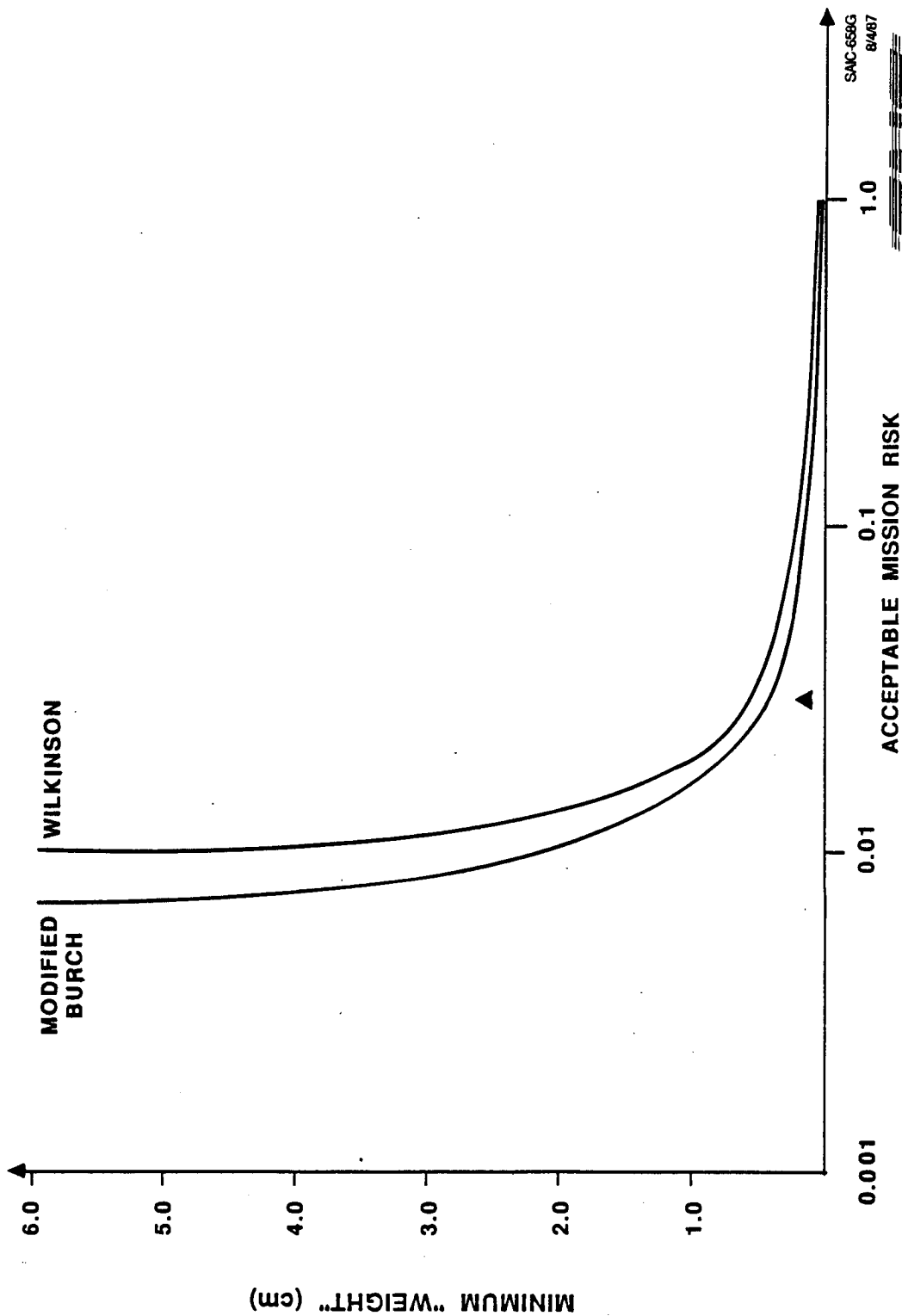
## **WILKINSON MORE SENSITIVE TO MISSION RISK THAN MODIFIED BURCH**

**SHOWN IS THE EFFECT OF INCREASING MISSION RISK (DECREASING PROBABILITY OF NO PENETRATION) ON OPTIMAL DESIGN FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS. NOTE THAT THE WILKINSON CURVE DOMINATES EXCEPT IN THE VERY HIGH MISSION RISK REGION.**

BM07-8/5

**SAIC**<sup>™</sup>

# WILKINSON MORE SENSITIVE TO MISSION RISK THAN MODIFIED BURCH



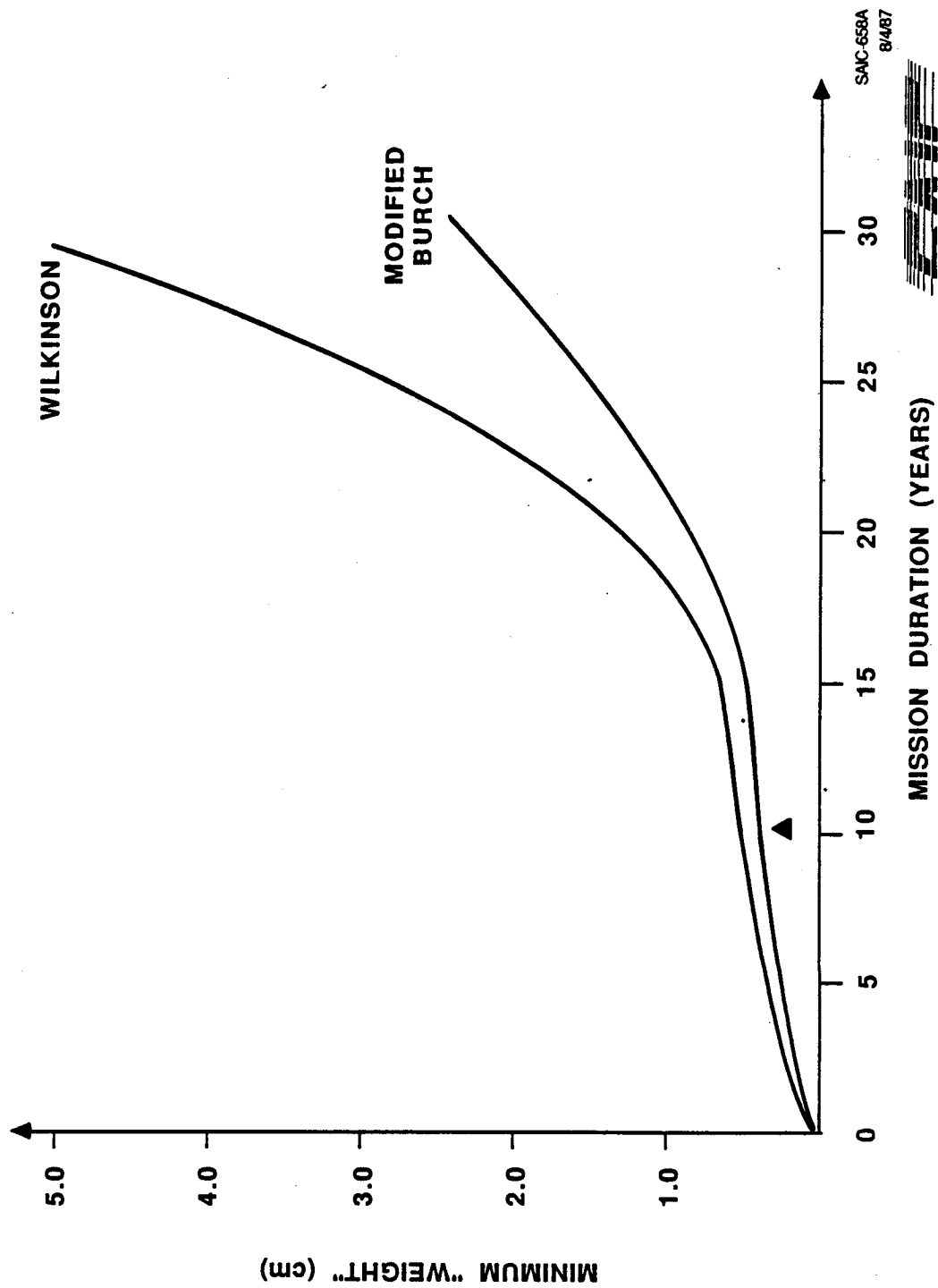
SAC-658G  
8/4/87

**SAIL**

## **GP REVEALS DIVERGENT SENSITIVITIES TO MISSION DURATION IN 20-30 YEAR RANGE**

**THE OPTIMAL DESIGN SENSITIVITY TO MISSION DURATION FOR THE  
MODIFIED BURCH AND WILKINSON SUBPREDICTORS IS SHOWN. EXCEPT  
FOR SHORT DURATION MISSIONS, THE WILKINSON CURVE DOMINATES IN  
AN INCREASING FASHION.**

# GP REVEALS DIVERGENT SENSITIVITIES TO MISSION DURATION IN 20 - 30 YEAR RANGE



SAC-658A  
8/487

**SAIL**

## GP DEFINES OPTIMAL DESIGN DISTRIBUTIONS

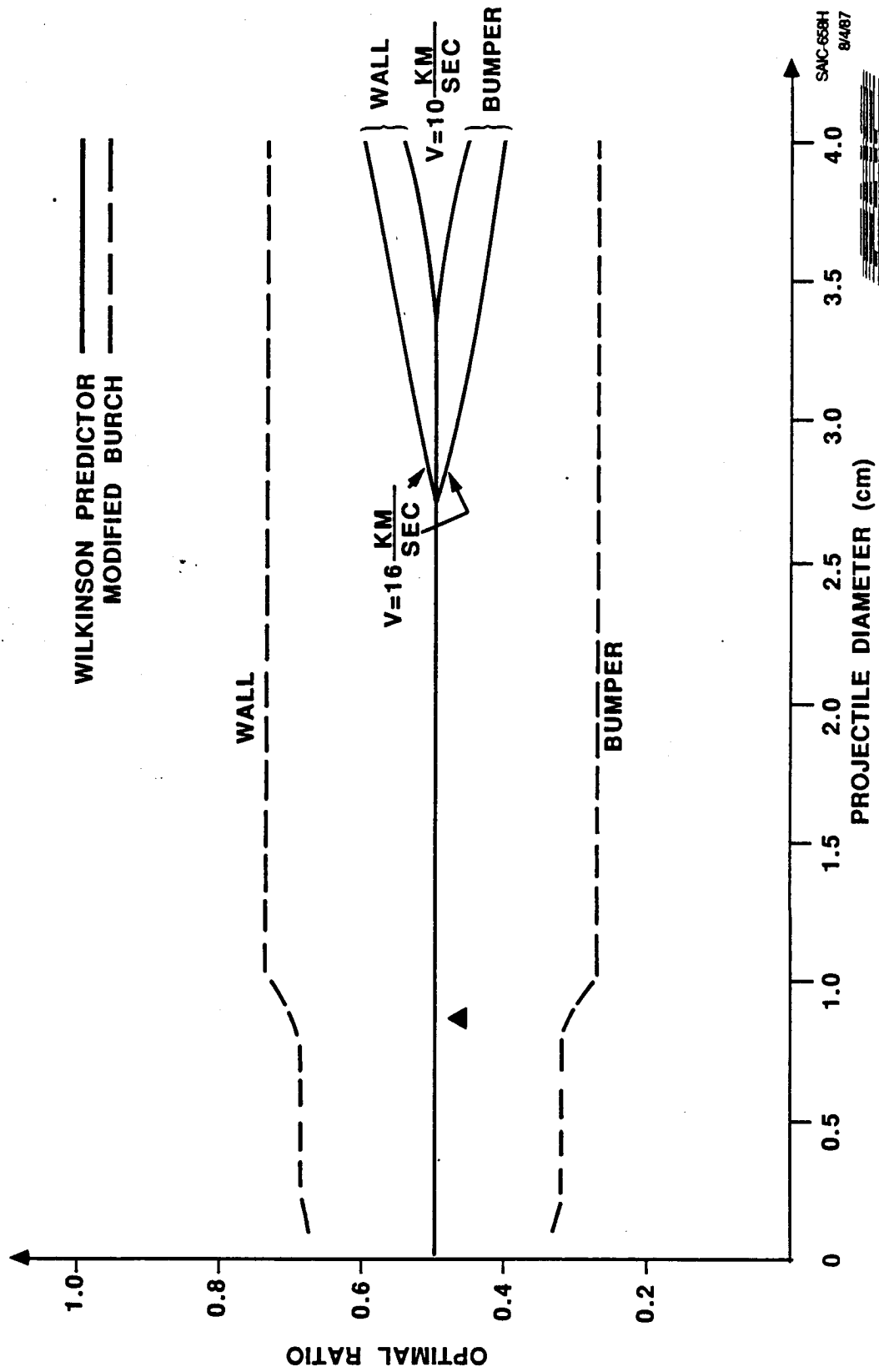
THE OPTIMAL RATIO AS A FUNCTION OF PROJECTILE DIAMETER FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS IS DEPICTED . THIS IS THE RATIO BETWEEN THE OPTIMAL BUMPER (OR WALL) THICKNESS AND THE TOTAL OPTIMAL THICKNESS. FOR THE MODIFIED BURCH PREDICTOR, THIS RATIO INDICATES AN OPTIMAL DISTRIBUTION OF 27%-33% BUMPER, 73%-67% WALL. FOR THE WILKINSON PREDICTOR, THE OPTIMAL DISTRIBUTION IS 50% BUMPER, 50% WALL, EXCEPT FOR LARGE DIAMETER PROJECTILES OR HIGHER VELOCITIES. IN THESE REGIONS, THE OPTIMAL DISTRIBUTION IS SKEWED TOWARD THE WALL THICKNESS.

BM09-8/5

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# GP DEFINES OPTIMAL DESIGN DISTRIBUTIONS



SAC 658H  
8/487



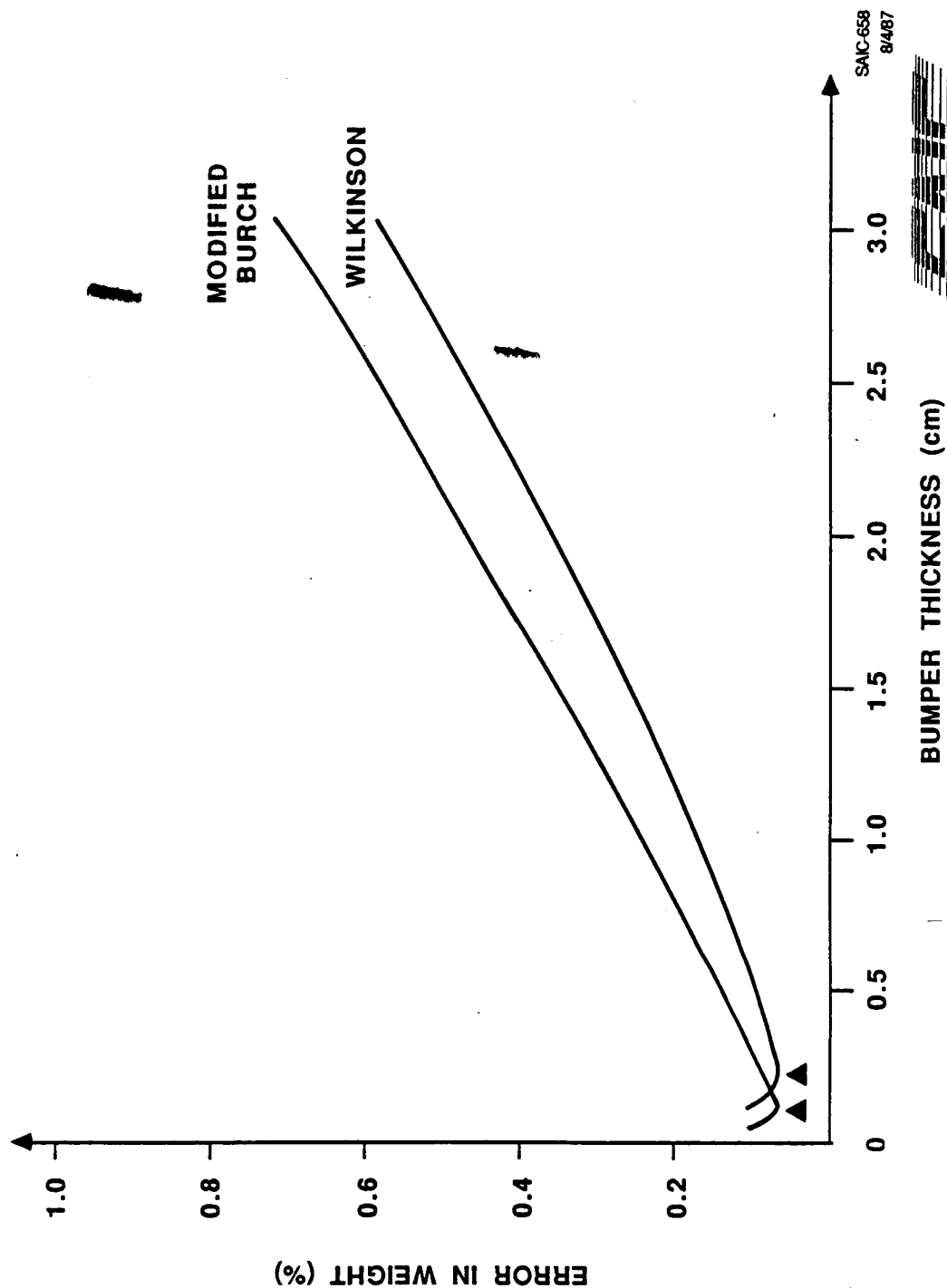
**LOW ERRORS ASSOCIATED WITH TWO  
DEGREE-OF-DIFFICULTY APPROXIMATION TO CMC WEIGHT**

SHOWN IS THE EFFECT OF BUMPER THICKNESS ON THE ERROR IN DESIGN WEIGHT ASSOCIATED WITH APPROXIMATING THE FIVE DEGREE-OF-DIFFICULTY GEOMETRIC PROGRAMMING PROBLEM WITH A TWO-TERM FUNCTION FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS. AS IN THE NYSMITH CASE, THE ERRORS ASSOCIATED WITH THIS APPROXIMATION ARE NEGLIGIBLE.

BM10-8/5

**SAIL**

**LOW ERRORS ASSOCIATED WITH TWO DEGREE-OF-DIFFICULTY  
APPROXIMATION TO CMC WEIGHT**



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# **SECTION V**

**GEOMETRIC PROGRAMMING APPLIED TO  
THE BOEING PREDICTOR.**

BM30-8/21



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## WHAT YOU WILL SEE IN SECTION V

- BASELINE DESIGN PARAMETERS FOR THE BOEING PREDICTOR
- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE BOEING PREDICTOR
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
  - PROJECTILE VELOCITY
  - BUMPER/WALL SEPARATION
  - PROJECTILE DIAMETER
  - MISSION RISK
  - MISSION DURATION
- THE OPTIMAL RATIO FOR BUMPER AND WALL AS A FUNCTION OF PROJECTILE DIAMETER

BM5-10/13



## **BASELINE DESIGN PARAMETERS**

**THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE BOEING  
PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRI-  
BUTION IS 16% BUMPER, 84% WALL.**

BM03-9/9





# BASELINE DESIGN PARAMETERS

## DESIGN ASSUMPTIONS

$P_o = 0.97$	(PROBABILITY OF NO PENETRATION)
$T = 10 \text{ YRS}$	(MISSION DURATION)
$A_d = 574 \text{ m}^2$	(DEBRIS AREA)
$A_m = 403 \text{ m}^2$	(METEOROID AREA)
$Alt = 500 \text{ km}$	(AVERAGE ALTITUDE)
$V_m = 20 \text{ km/sec}$	(AVERAGE METEOROID VELOCITY)
$V_D = 10 \text{ km/sec}$	(AVERAGE DEBRIS VELOCITY)
$\rho_m = 0.5 \text{ gm/cm}^3$	(METEOROID DENSITY)
$\rho_D = 2.81 \text{ gm/cm}^3$	(DEBRIS DENSITY)
$S = 10 \text{ cm}$	(BUMPER/WALL SEPARATION)
$\rho_1 = 2.8 \text{ gm/cm}^3$	
$E_1 = 7.239 \times 10^{11} \text{ gm/cm-sec}^2$	
$Sy_1 = 7344000 \text{ lb/ft}^2 \text{ (51 Ksi)}$	
$\rho_2 = \rho_1$	
$Sy_2 = Sy_1$	
$L_2 = 0.401$	
$\theta = 0 \text{ degrees}$	

BM06-8/21

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## BASELINE DESIGN PARAMETERS (CONT'D)

### OPTIMAL DESIGN (BALLISTIC LIMIT)

#### BUMPER

$$t_{10} = 0.09 \text{ cm } (.04 \text{ in})$$

#### WALL

$$t_{20} = 0.49 \text{ cm } (.19 \text{ in})$$

$$\text{CMC weight} = 2979 \text{ Kg } (6554 \text{ lb})$$

BM06A-8/21

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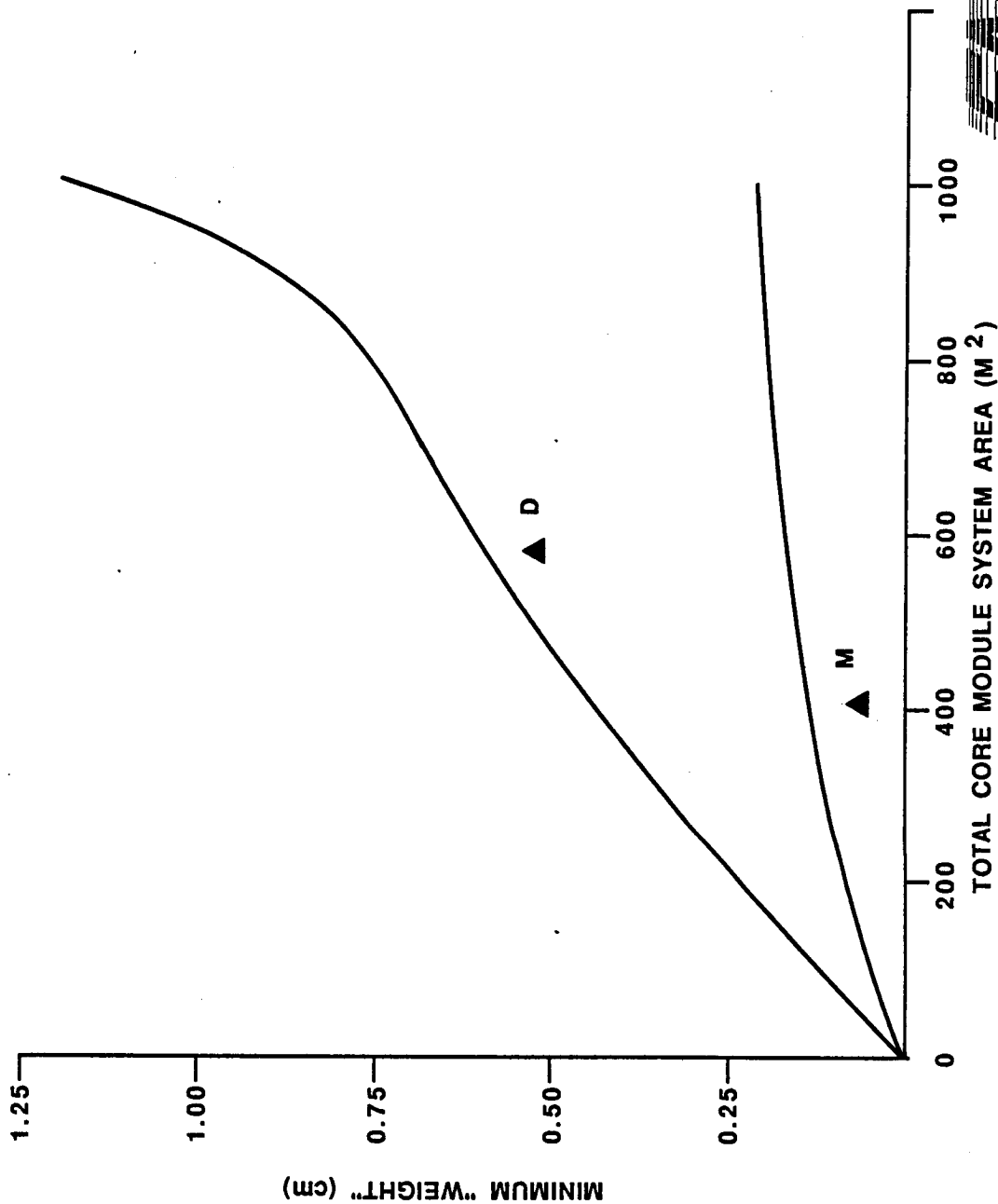
## **DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE ESTIMATE OF METEOROID EFFECT**

SHOWN IS THE EFFECT OF CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE DEBRIS AND METEOROID SCENARIOS OF THE BOEING PREDICTOR. NOTE THAT EVEN THOUGH THE METEOROID PROJECTILE DENSITY WAS ASSUMED TO BE 2.81 GM/CUBIC CM (BURCH HAS NO DENSITY PARAMETER), THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN.

BM07-8/11

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DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE  
ESTIMATE OF METEOROID EFFECT



SAIC-664  
8/11/87



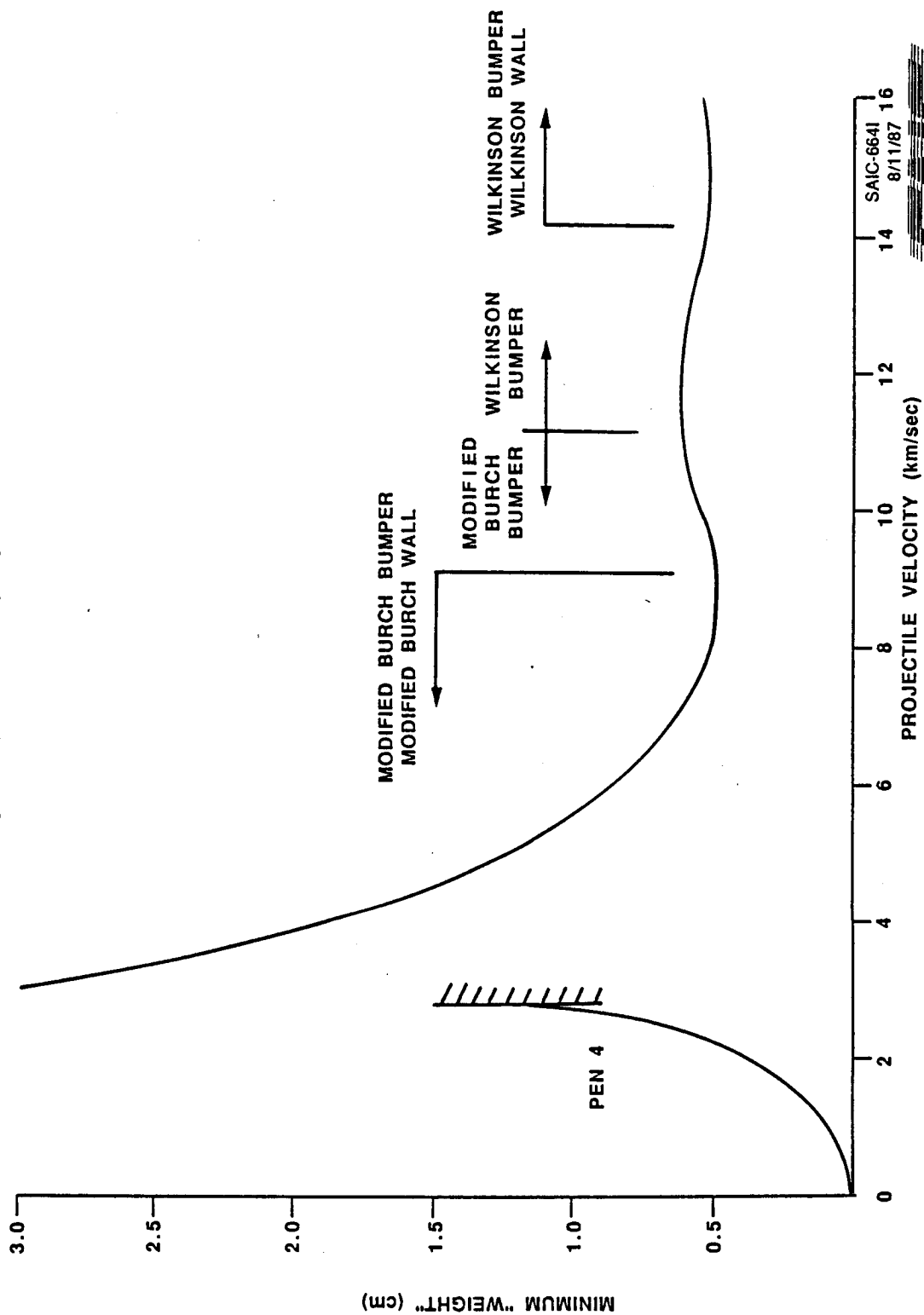
## GP REVEALS COMPLEX DESIGN SENSITIVITY TO VELOCITY FOR BOEING PREDICTOR

THE EFFECT OF PROJECTILE VELOCITY ON OPTIMAL DESIGN IS SHOWN FOR THE BOEING PREDICTOR. THE PEN4 PREDICTOR IS SEGREGATED FROM THE OTHER TWO BOEING PREDICTORS AS IT IS ONLY VALID UP TO 2.8 km/sec. ON COMPARISON WITH THE CORRESPONDING TRADE FOR THE THREE BOEING SUBPREDICTORS, IT IS EASY TO SEE THAT THE MODIFIED BURCH OPTIMAL DESIGN DOMINATES BETWEEN 2.8 km/sec AND 9 km/sec, AND THE WILKINSON OPTIMAL DESIGN DOMINATES FROM 14 TO 16 km/sec. BETWEEN 9 AND 11 km/sec, THE MODIFIED BURCH OPTIMAL BUMPER DESIGN IS CHOSEN ALONG WITH THE WILKINSON WALL DESIGN INDUCED BY THIS BUMPER. FROM 11 TO 14 km/sec, THE ROLES OF THE TWO PREDICTORS ARE REVERSED.

BM08-8/11

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# GP REVEALS COMPLEX DESIGN SENSITIVITY TO VELOCITY FOR BOEING PREDICTOR



SAIC-6641  
8/11/87 16



**GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION  
FOR THE BOEING PREDICTOR**

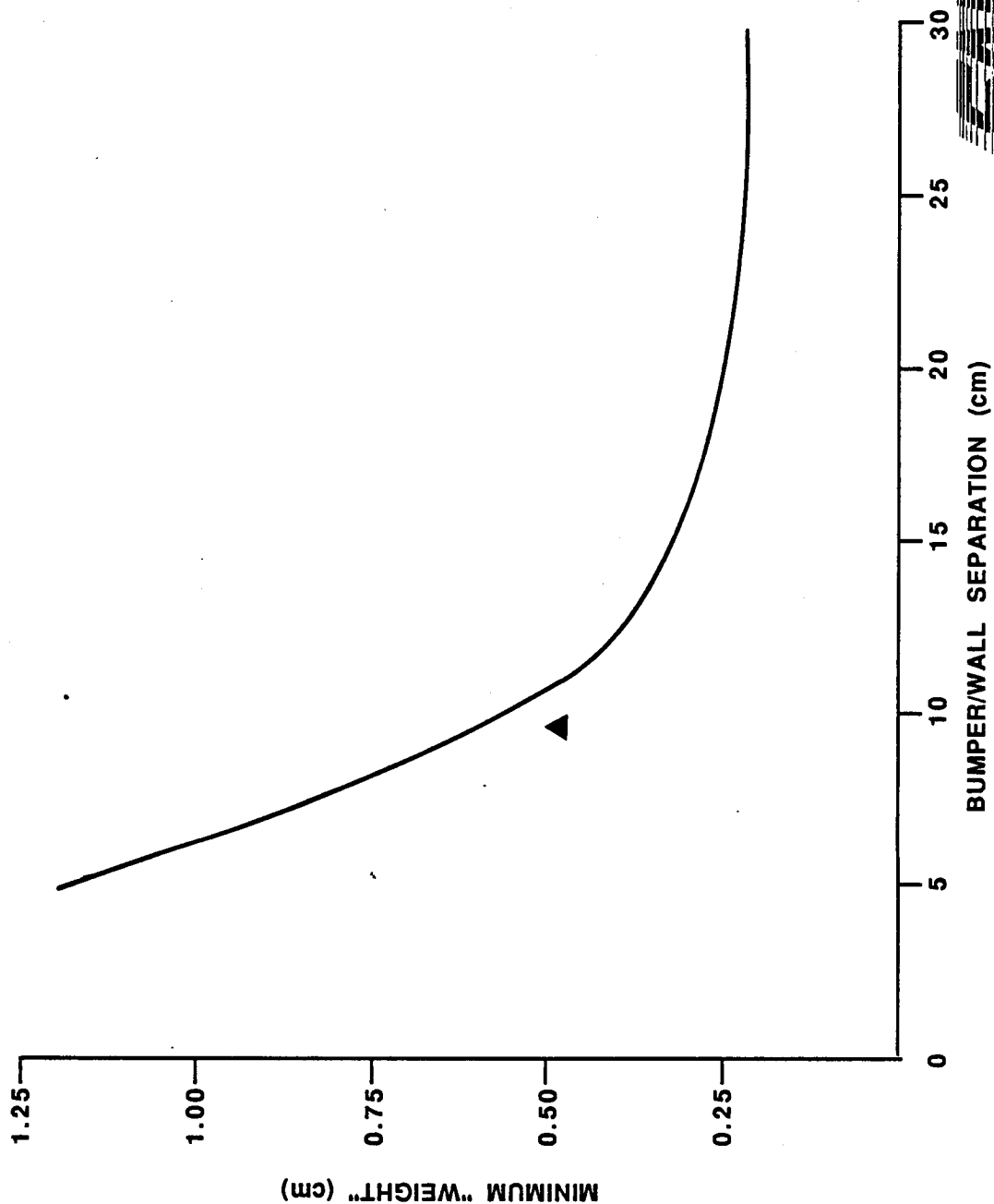
**SHOWN IS THE DESIGN SENSITIVITY TO BUMPER/WALL SEPARATION FOR  
THE BOEING PREDICTOR. NOTE THE LARGE INCENTIVE (A REDUCTION  
IN DESIGN OF 40%) FOR INCREASING THE BUMPER/WALL SEPARATION  
BY 50% TO 15CM.**

BM09-8/11





GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION  
FOR THE BOEING PREDICTOR



SAIC-664F  
8/11/87



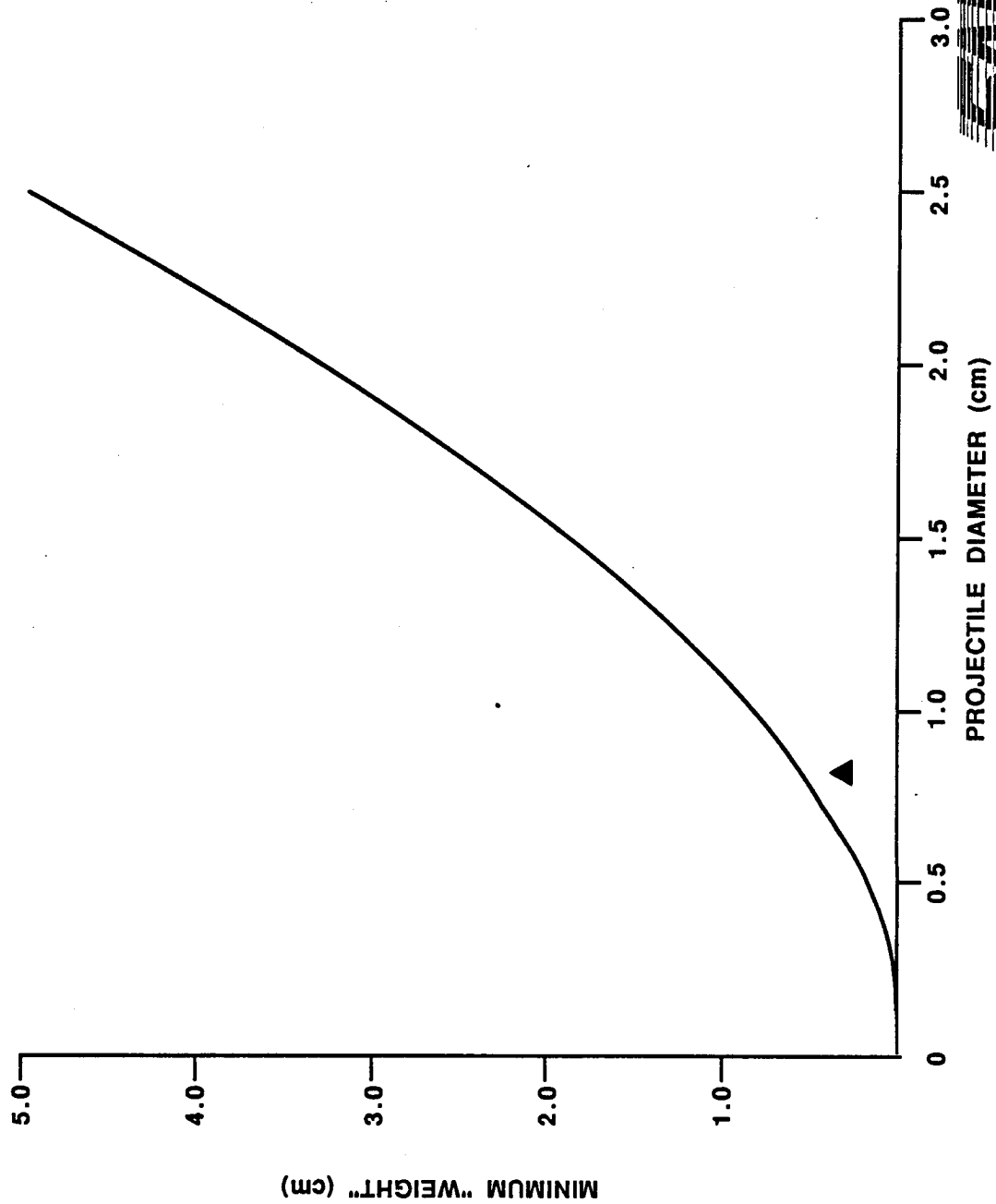
## **LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR**

**SHOWN IS THE SENSITIVITY OF OPTIMAL DESIGN TO PROJECTILE DIAMETER FOR THE BOEING PREDICTOR. NOTE THE LARGE SENSITIVITY FOR PROJECTILE DIAMETERS GREATER THAN ABOUT 1CM, WHERE THE SLOPES INCREASE TO 2-3.**

BM10-8/11

**SAIC**<sup>TM</sup>

# LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR



SAIC-664A  
8/11/87



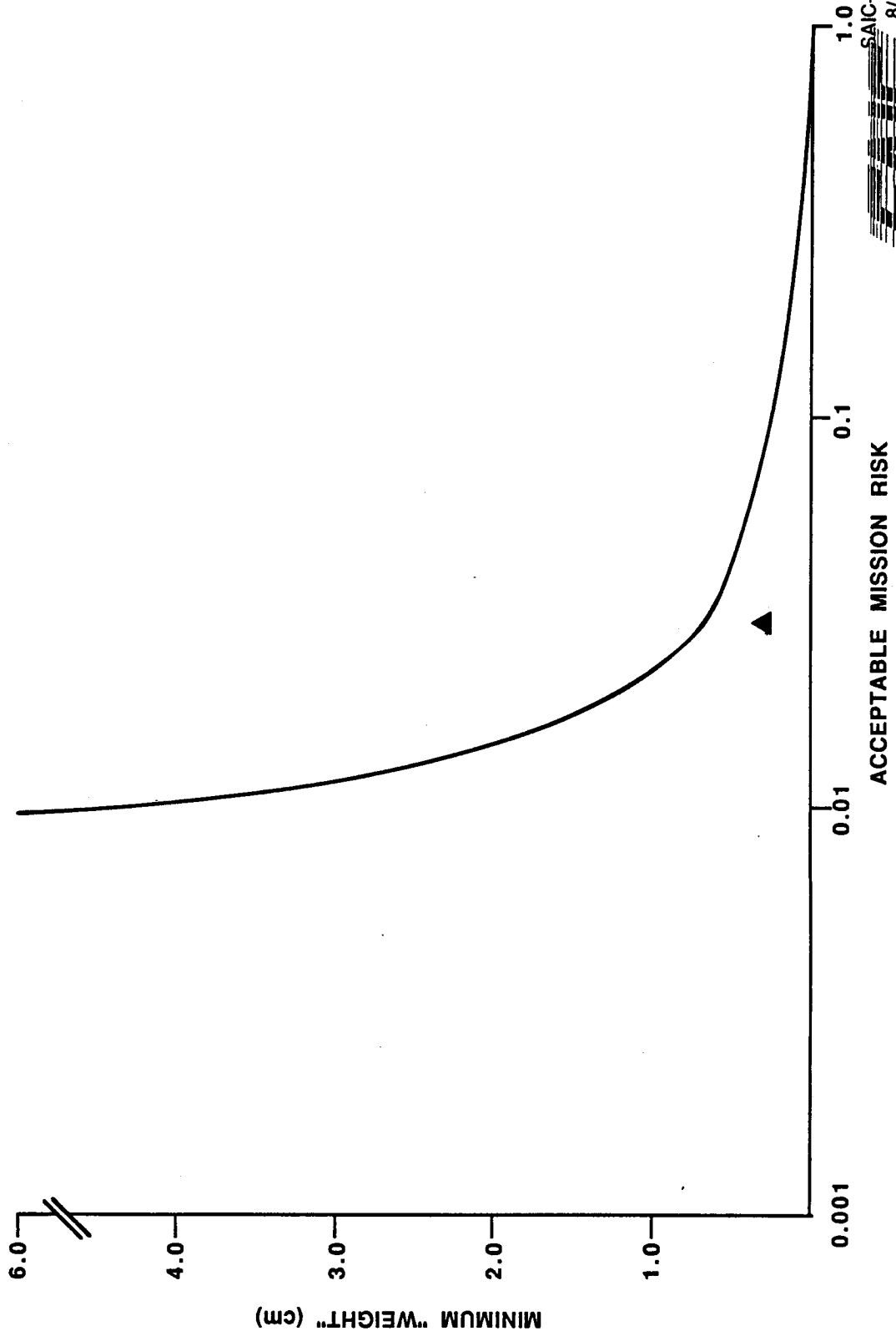
**LARGE DESIGN PENALTY INDUCED BY INCREASE IN  
PROBABILITY OF NO PENETRATION: BOEING PREDICTOR**

**THE EFFECT OF ACCEPTABLE MISSION RISK ON OPTIMAL DESIGN IS SHOWN  
FOR THE BOEING PREDICTOR. NOTE THE DRASTIC INCREASE IN OPTIMAL  
DESIGN FOR PROBABILITY OF NO PENETRATION ABOVE 0.97.**

BM11-8/11

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**LARGE DESIGN PENALTY INDUCED BY INCREASE IN  
PROBABILITY OF NO PENETRATION: BOEING PREDICTOR**



SAIC-664H  
8/11/87



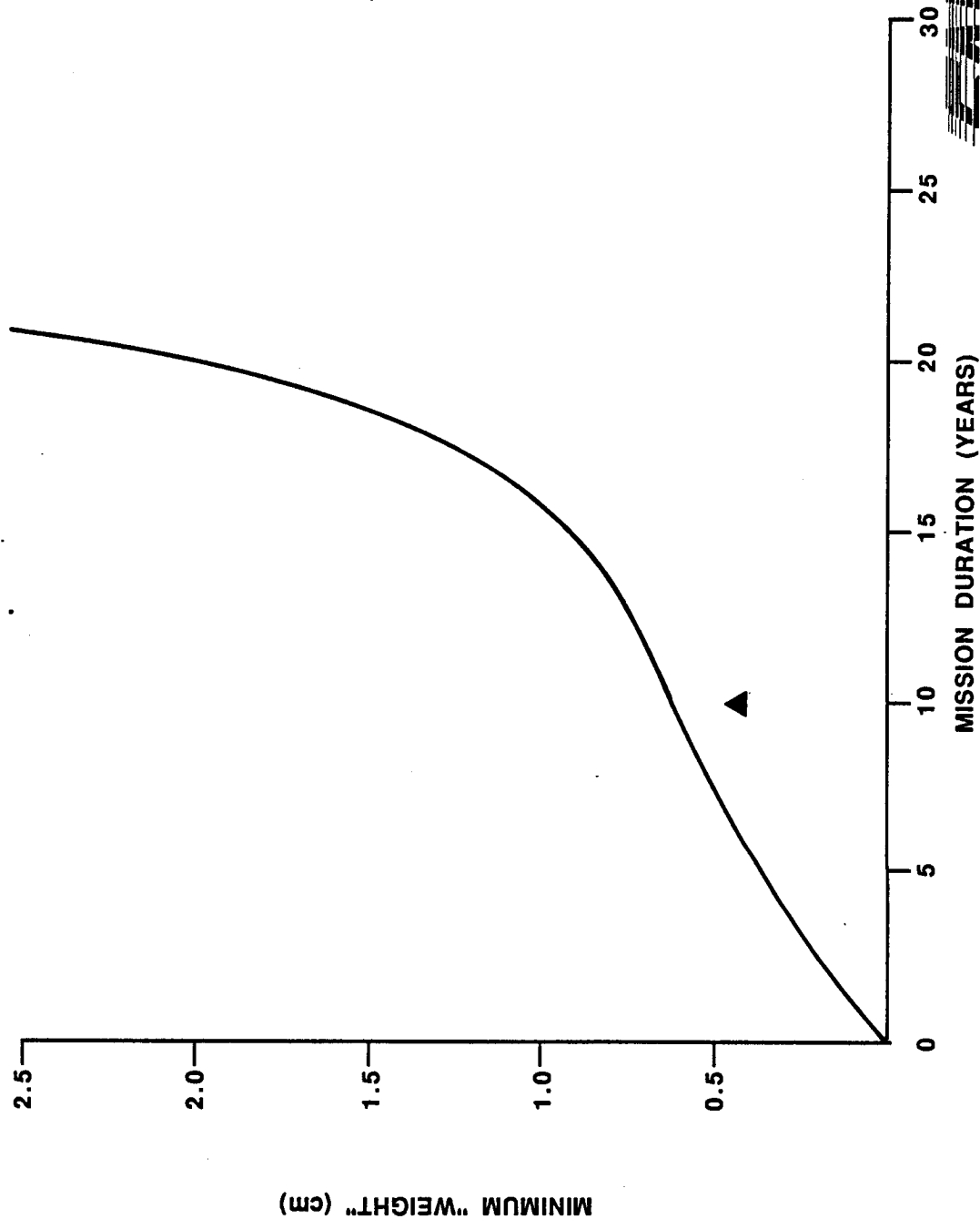
## **SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION MISSIONS: BOEING PREDICTOR**

**THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR THE BOEING  
PREDICTOR IS SHOWN. THE INFLECTION AT 15 YEARS, AND THE SHARP  
INCREASE IN SLOPE AT ABOUT 22 YEARS RAISE SERIOUS DESIGN  
QUESTIONS FOR MISSION PLANNERS ABOUT LONG-DURATION MISSIONS.**

BM12-8/11

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**SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION  
MISSIONS: BOEING PREDICTOR**



SAIC-664D  
8/11/87



## **GP PROVIDES OPTIMAL DISTRIBUTION FOR BOEING PREDICTOR**

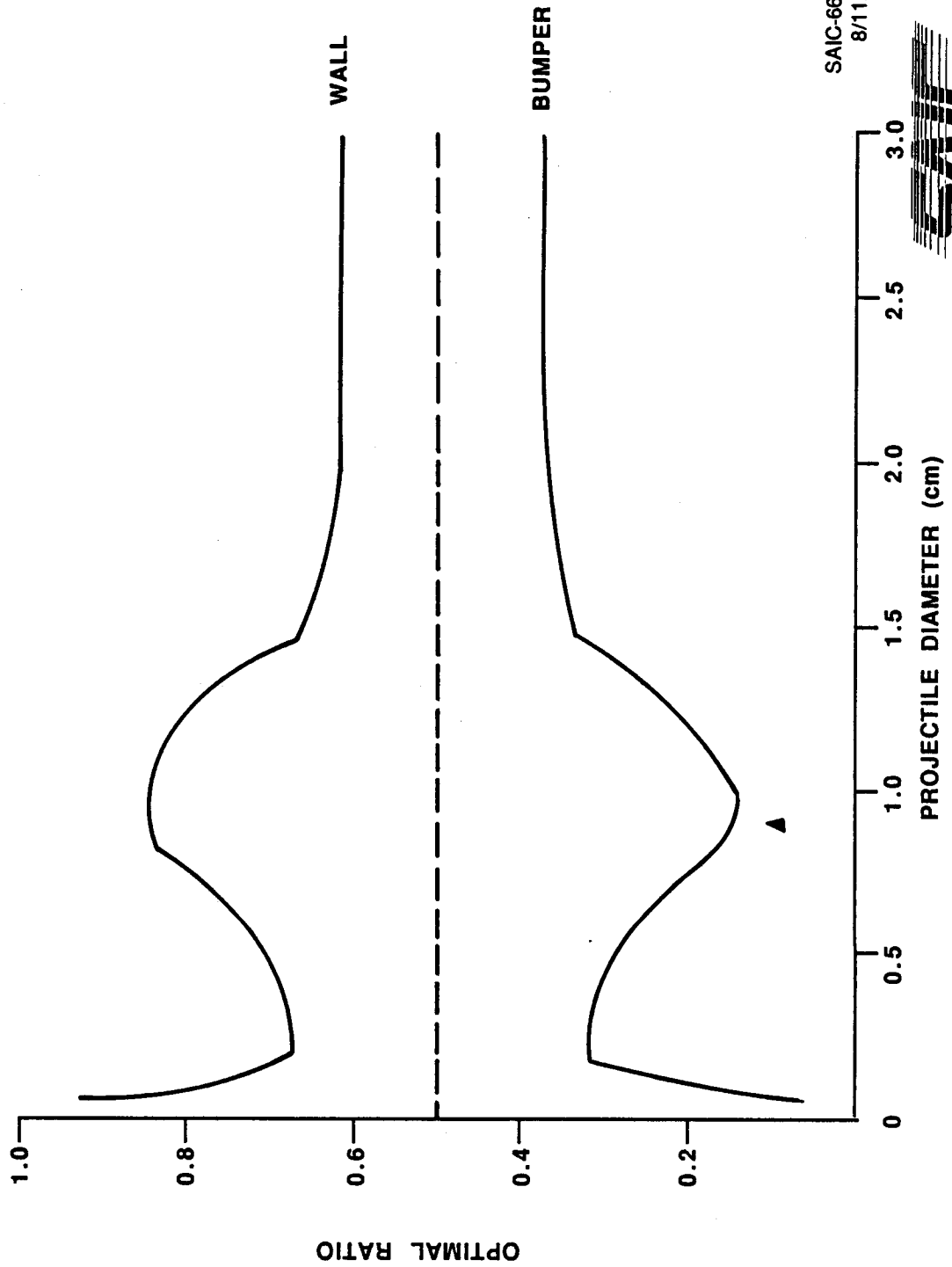
THE OPTIMAL RATIO AS A FUNCTION OF PROJECTILE DIAMETER IS DEPICTED FOR THE BOEING PREDICTOR. THIS IS THE RATIO OF OPTIMAL BUMPER (WALL) THICKNESS TO TOTAL OPTIMAL THICKNESS, AND IS QUITE NON-LINEAR (AND NONCONSTANT). THIS NONLINEARITY HAS TO DO WITH THE INTERACTION OF THE MODIFIED BURCH AND WILKINSON PREDICTORS.

BM13-8/11

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GP PROVIDES OPTIMAL DISTRIBUTION  
FOR BOEING PREDICTOR



SAIC-664C  
8/11/87



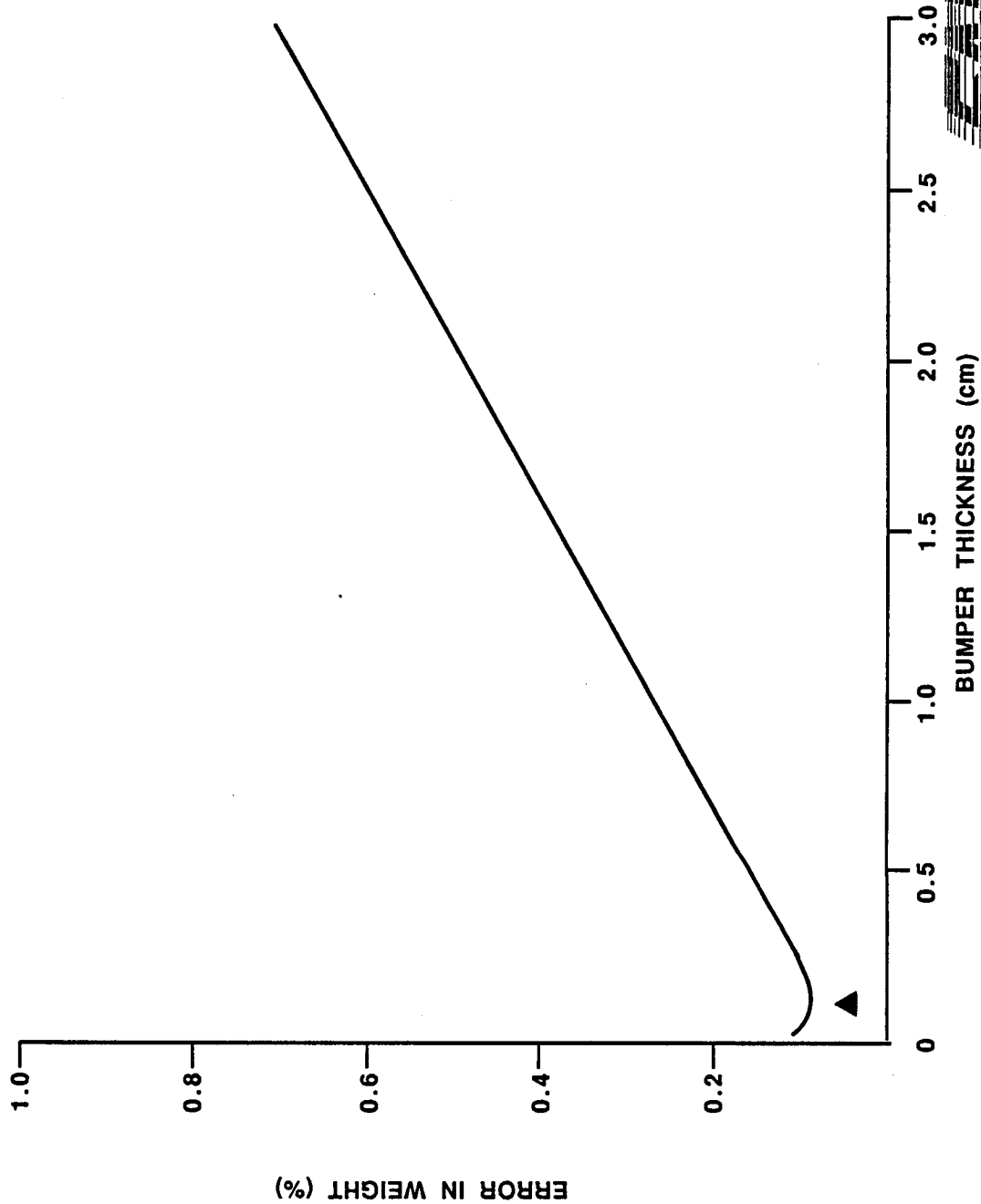
## **SMALL ERRORS ASSOCIATED WITH REDUCTION OF DEGREE-OF-DIFFICULTY FOR BOEING PREDICTOR**

**THE ERROR IN CORE MODULE CONFIGURATION WEIGHT AS A  
FUNCTION OF BUMPER THICKNESS IS SHOWN FOR THE BOEING  
PREDICTOR. THIS REPRESENTS THE ERROR INDUCED BY  
REDUCING THE GP OPTIMIZATION PROBLEM FROM 5  
DEGREES-OF-DIFFICULTY TO TWO. NOTE THAT THE ERROR IS  
NEGLECTIBLE IN A LARGE NEIGHBORHOOD OF THE BASELINE  
DESIGN.**

BM14-8/11

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SMALL ERRORS ASSOCIATED WITH REDUCTION OF  
DEGREE-OF-DIFFICULTY FOR BOEING PREDICTOR



SAIC-664G  
8/11/87



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# **SECTION VI**

**GEOMETRIC PROGRAMMING APPLIED TO  
THE VELOCITY-INTEGRATED BOEING  
PREDICTOR.**

BM31-8/21

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## WHAT YOU WILL SEE IN SECTION VI

- ALGORITHM AND BASELINE DESIGN PARAMETERS FOR THE VELOCITY-INTEGRATED BOEING SUBPREDICTORS
- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE BOEING SUBPREDICTORS
- THE SENSITIVITY OF OPTIMAL DESIGN TO ORBITAL INCLINATION
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
  - PROJECTILE VELOCITY
  - BUMPER/WALL SEPARATION
  - PROJECTILE DIAMETER
  - MISSION RISK
  - MISSION DURATION
- THE OPTIMAL RATIO FOR BUMPER AND WALL AS A FUNCTION OF PROJECTILE DIAMETER
- COST EXCURSIONS
- SUMMARY OF PREDICTOR RESULTS

BM6 10/13

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## **BASELINE DESIGN PARAMETERS**

**THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE VELOCITY-  
INTEGRATED BOEING PREDICTOR ARE SHOWN. NOTE THAT THE BASE-  
LINE OPTIMAL DISTRIBUTION IS 21% BUMPER, 79% WALL.**

BM04-9/9





# BASELINE DESIGN PARAMETERS

DESIGN ASSUMPTIONS	
$P_o$	= 0.97 (PROBABILITY OF NO PENETRATION)
$T$	= 10 yrs (MISSION DURATION)
$A_d$	= 574 m <sup>2</sup> (DEBRIS AREA)
$A_m$	= 403 m <sup>2</sup> (METEOROID AREA)
Alt	= 500 km (AVERAGE ALTITUDE)
$\rho_m$	= 0.5 gm/cm <sup>3</sup> (METEOROID DENSITY)
$\rho_D$	= 2.81 gm/cm <sup>3</sup> (DEBRIS DENSITY)
$S$	= 10 cm (BUMPER/WALL SEPARATION)
$\rho_1$	= 2.81 gm/cm <sup>3</sup>
$E_1$	= 7.239x10 <sup>11</sup> gm/cm-sec <sup>2</sup>
$Sy_1$	= 7344000 lb/ft <sup>2</sup> (51 Ksi)
$\rho_2$	= $\rho_1$
$Sy_2$	= $Sy_1$
$L_2$	= 0.401
$\theta$	= 0 degrees

OPTIMAL DESIGN (BALLISTIC LIMIT)	
<u>BUMPER</u>	
$t_{10}$	= 0.16cm (0.06 ln)
<u>WALL</u>	
$t_{20}$	= 0.59 cm (0.23 ln)
CMC weight	= 3837 Kg (8441 lb)

BM07-8/21



## VELOCITY PROBABILITY DISTRIBUTIONS

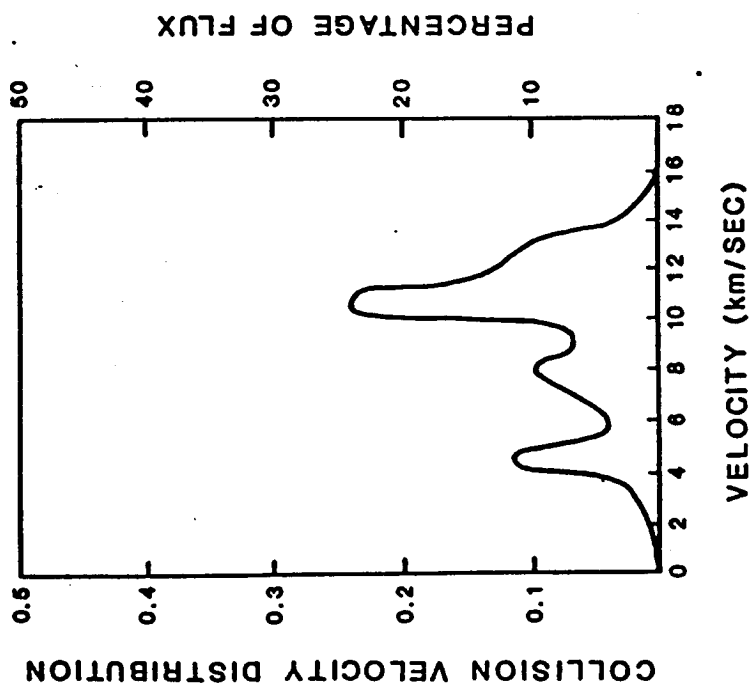
SHOWN IS THE 500km VELOCITY PROBABILITY DISTRIBUTION FOR 30 AND 60 DEGREE INCLINATIONS FROM DON KESSLER'S JSC-20001. NOTE THAT THE 60 DEGREE INCLINATION DISTRIBUTION IS HIGHLY SKEWED TOWARD THE HIGHER VELOCITIES.

**SAIC**<sup>TM</sup>

## VELOCITY PROBABILITY DISTRIBUTIONS

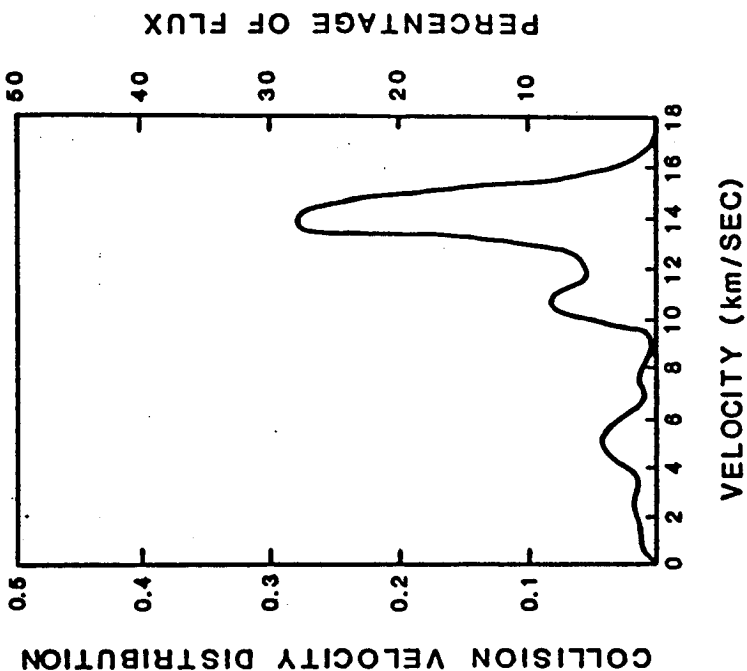
ALTITUDE: 500 km

INCLINATION: 30°



ALTITUDE: 500 km

INCLINATION: 60°



**SAIC**

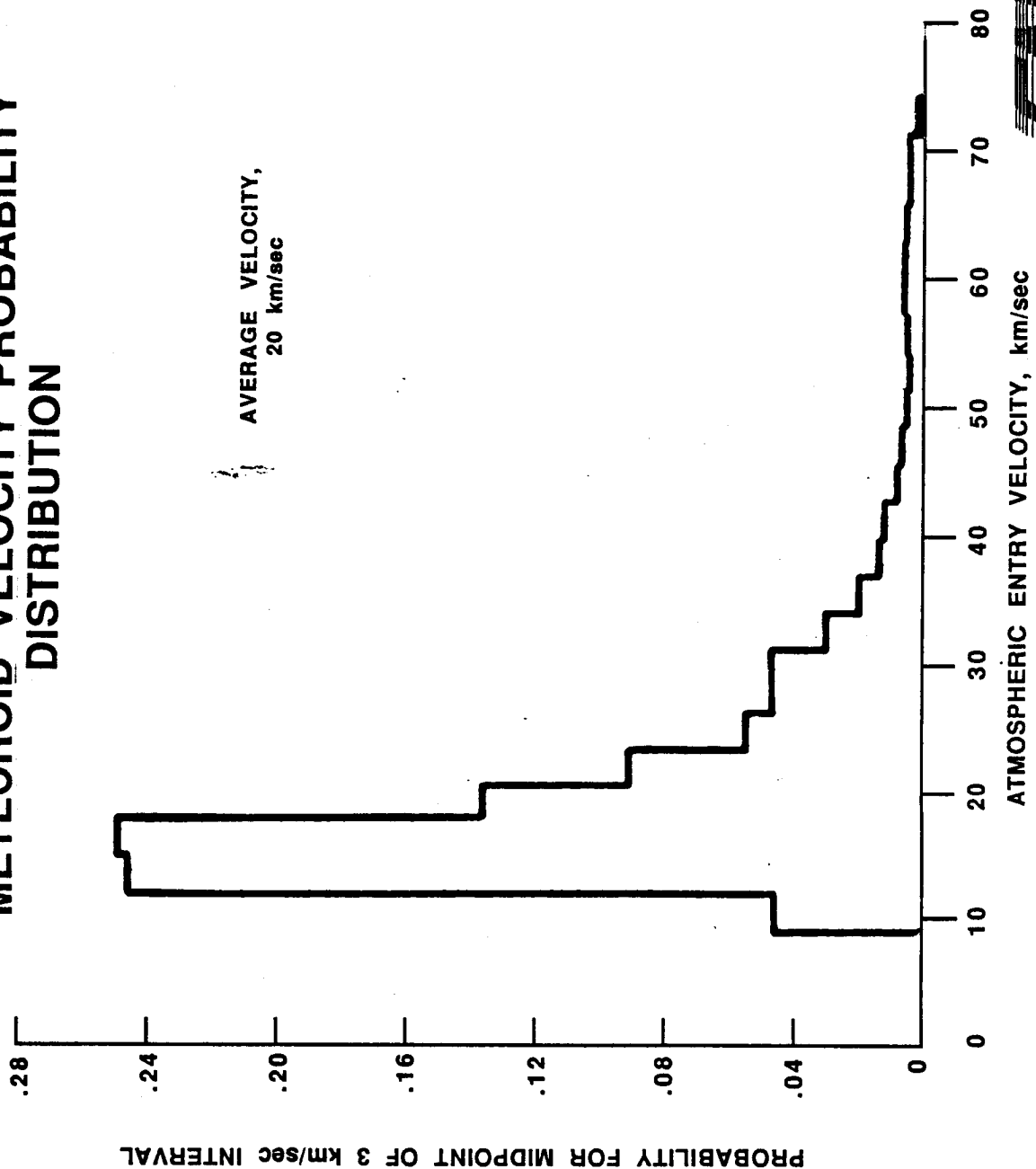
# **METEOROID VELOCITY PROBABILITY DISTRIBUTION**

**AN APPROXIMATE VELOCITY PROBABILITY  
DISTRIBUTION FOR THE METEOROID SCENARIO  
IS SHOWN. AVERAGE VELOCITY IS ROUGHLY  
20 KM/SEC. THIS DISTRIBUTION IS REFERENCED  
IN BURT COUR-PALAIS "METEOROID ENVIRONMENT  
MODEL - 1969 (NEAR-EARTH TO LUNAR SURFACE,"  
NASA SP-8013, MARCH 1969.**

BM14-8/21

**SAIC**<sup>®</sup>

# METEOROID VELOCITY PROBABILITY DISTRIBUTION



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## **ALGORITHM FOR VELOCITY-INTEGRATED BOEING PREDICTOR**

- (1) DETERMINE VELOCITY INTERVALS.**
- (2) FOR MIDPOINT OF INTERVAL, DETERMINE OPTIMAL DESIGN FOR BOEING PREDICTOR.**
- (3) MULTIPLY OPTIMAL DESIGN BY APPROPRIATE VELOCITY PROBABILITY AT INTERVAL MIDPOINT; THEN MULTIPLY BY INTERVAL LENGTH.**
- (4) SUM THE PRODUCT IN (3) OVER THE ENTIRE RANGE OF VELOCITIES TO DETERMINE THE OVERALL OPTIMAL DESIGN.**

## **DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE ESTIMATE OF METEOROID EFFECT**

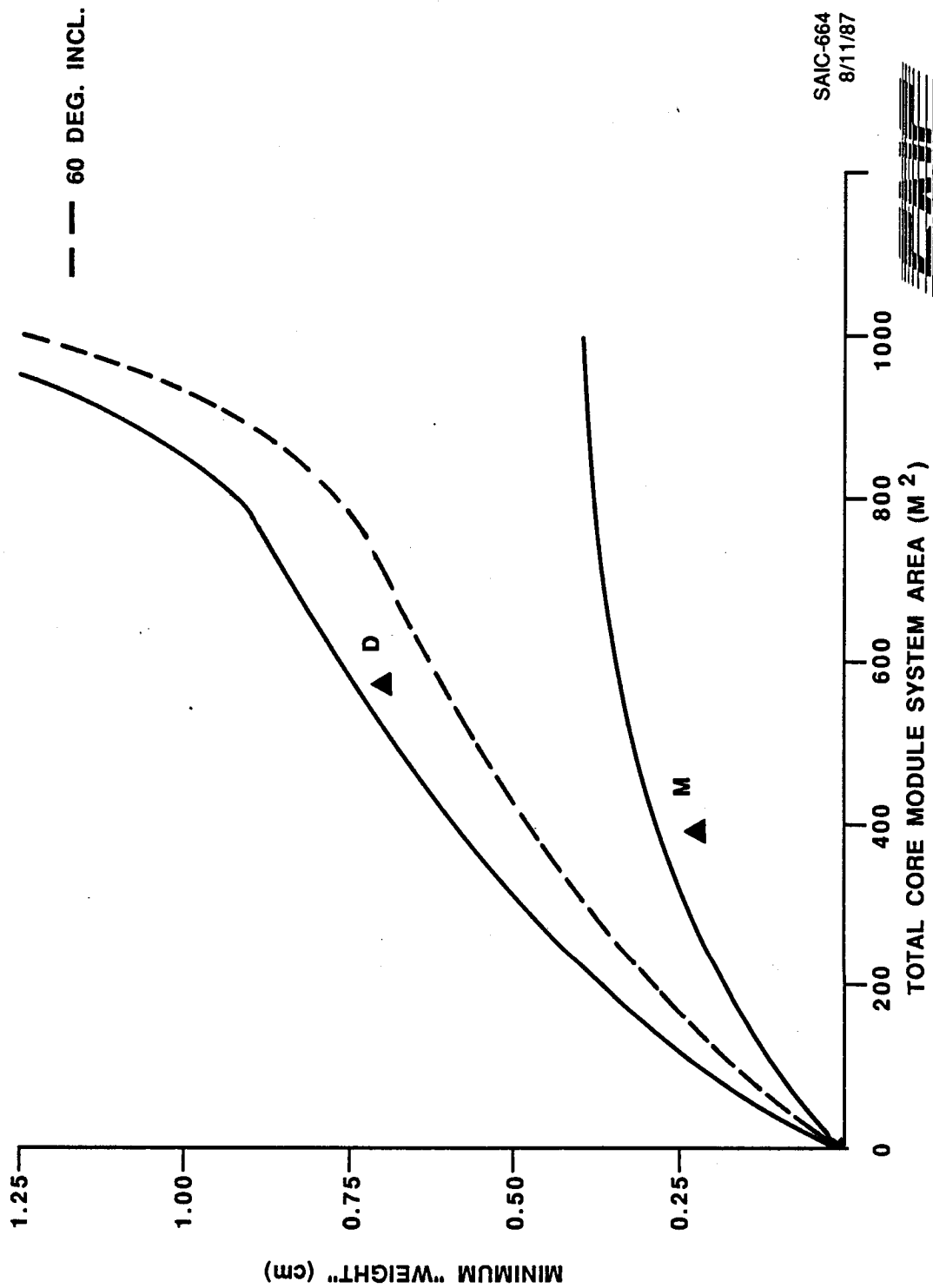
SHOWN IS THE EFFECT OF CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE DEBRIS AND METEOROID SCENARIOS OF THE BOEING PREDICTOR FOR THE BASELINE 30 DEGREE INCLINATION AND A 60 DEGREE INCLINATION. NOTE THAT EVEN THOUGH THE METEOROID PROJECTILE DENSITY WAS ASSUMED TO BE 2.81 GM/CUBIC CM (BURCH HAS NO DENSITY PARAMETER), THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN. FURTHERMORE, NOTE THE 20% DECREASE IN DESIGN INDUCED BY A 60° INCLINATION.

BM01-8/11

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**DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE  
ESTIMATE OF METEOROID EFFECT**



SAIC-664  
8/11/87



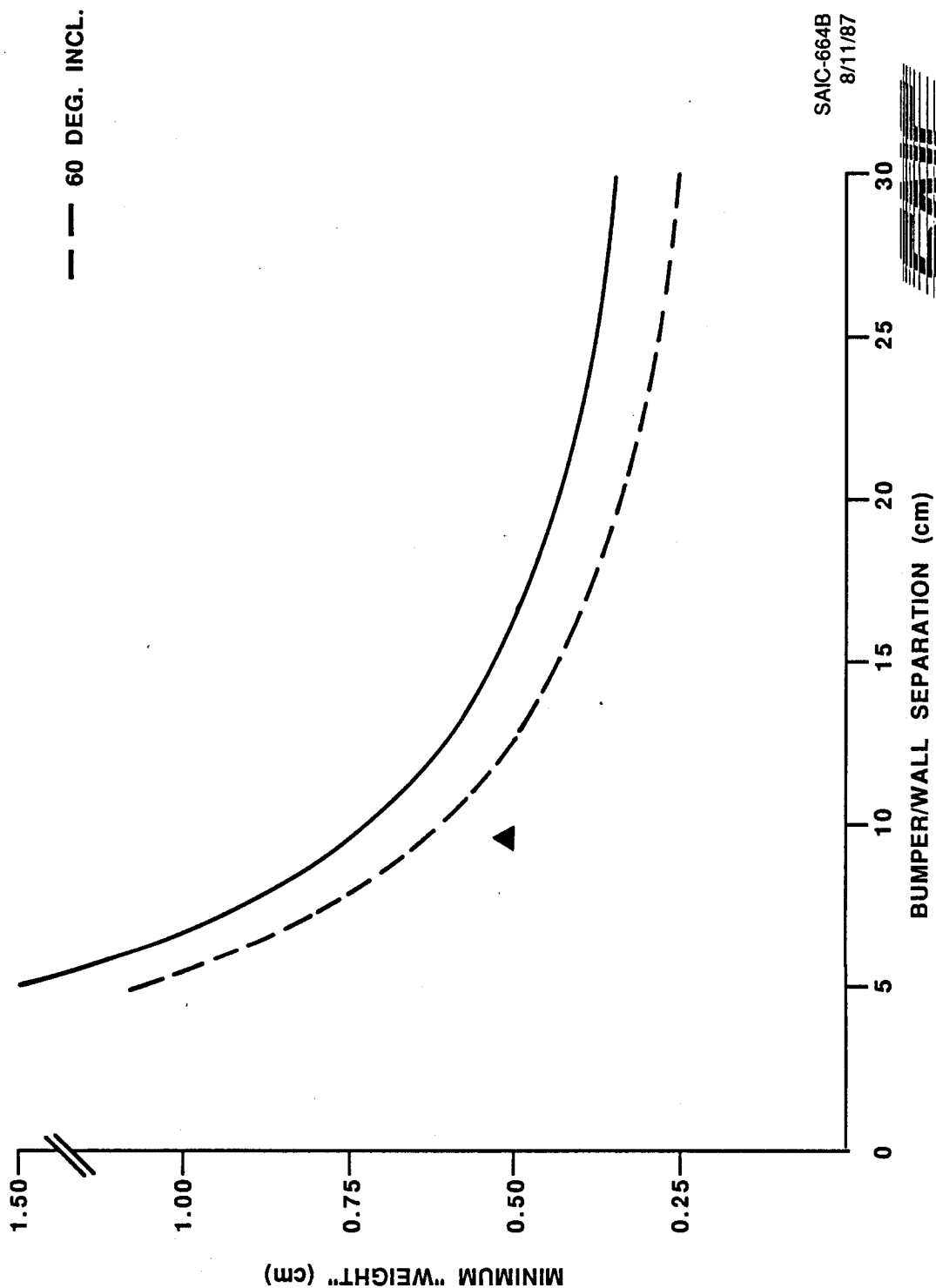
**GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION  
FOR THE BOEING PREDICTOR**

**THE DESIGN SENSITIVITY TO BUMPER/WALL SEPARATION FOR THE BOEING  
PREDICTOR IS SHOWN FOR 30 AND 60 DEGREE INCLINATIONS. NOTE  
THE LARGE INCENTIVE (A REDUCTION IN DESIGN OF 40%) FOR INCREASING  
THE BUMPER/WALL SEPARATION BY 50% TO 15 CM.**

BM02-8/11

**SAIC®**

GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION  
FOR THE BOEING PREDICTOR



SAIC-664B  
8/11/87



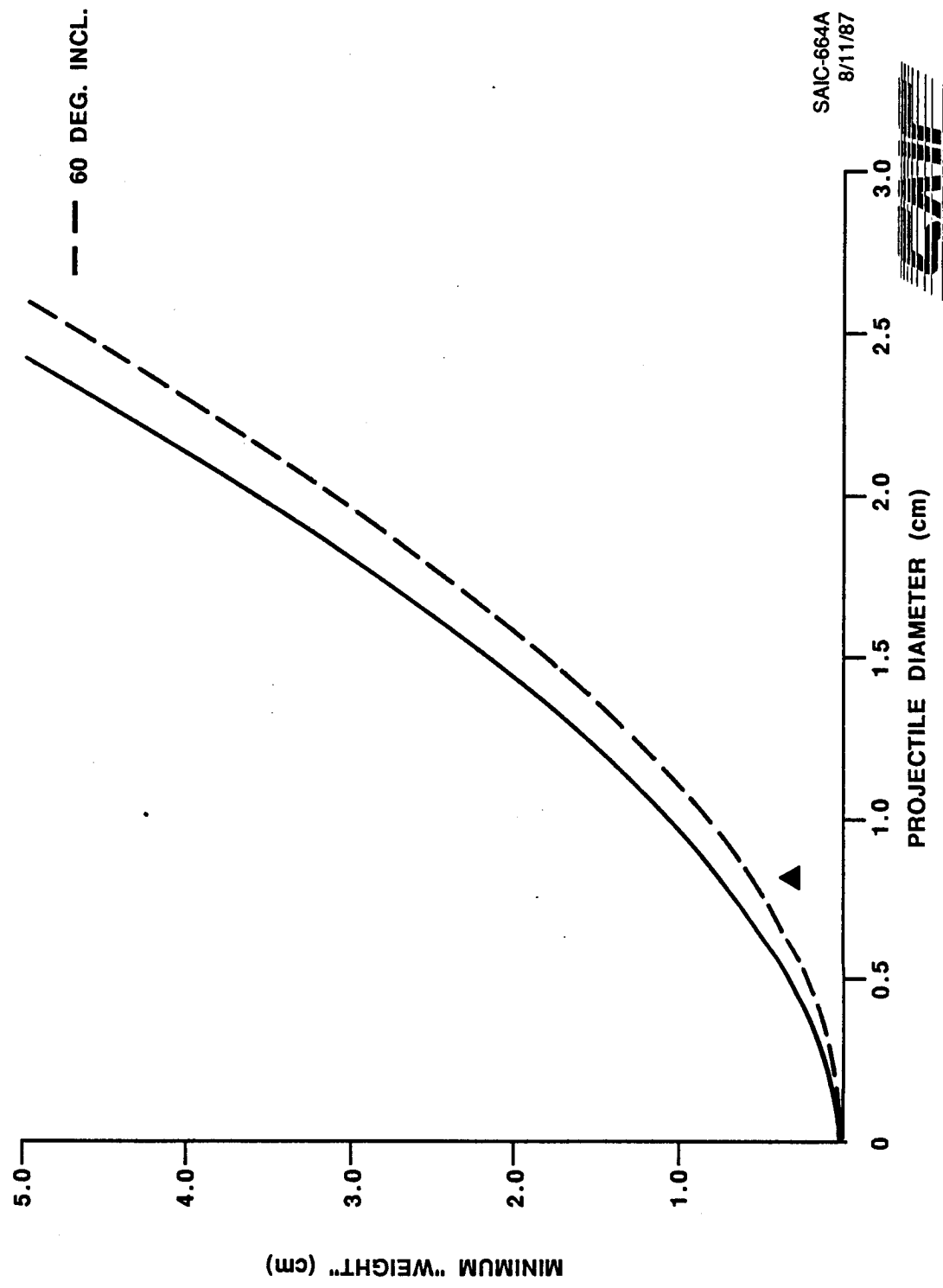
## **LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR**

**THE SENSITIVITY OF OPTIMAL DESIGN TO PROJECTILE DIAMETER FOR THE  
BOEING PREDICTOR IS SHOWN FOR 30 AND 60 DEGREE INCLINATIONS. NOTE  
THE LARGE SENSITIVITY FOR PROJECTILE DIAMETERS GREATER THAN ABOUT  
1 CM, WHERE THE SLOPES INCREASE TO 2-3.**

BM03-8/11

**SAIC<sup>®</sup>**

# LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR



SAIC-664A  
8/11/87



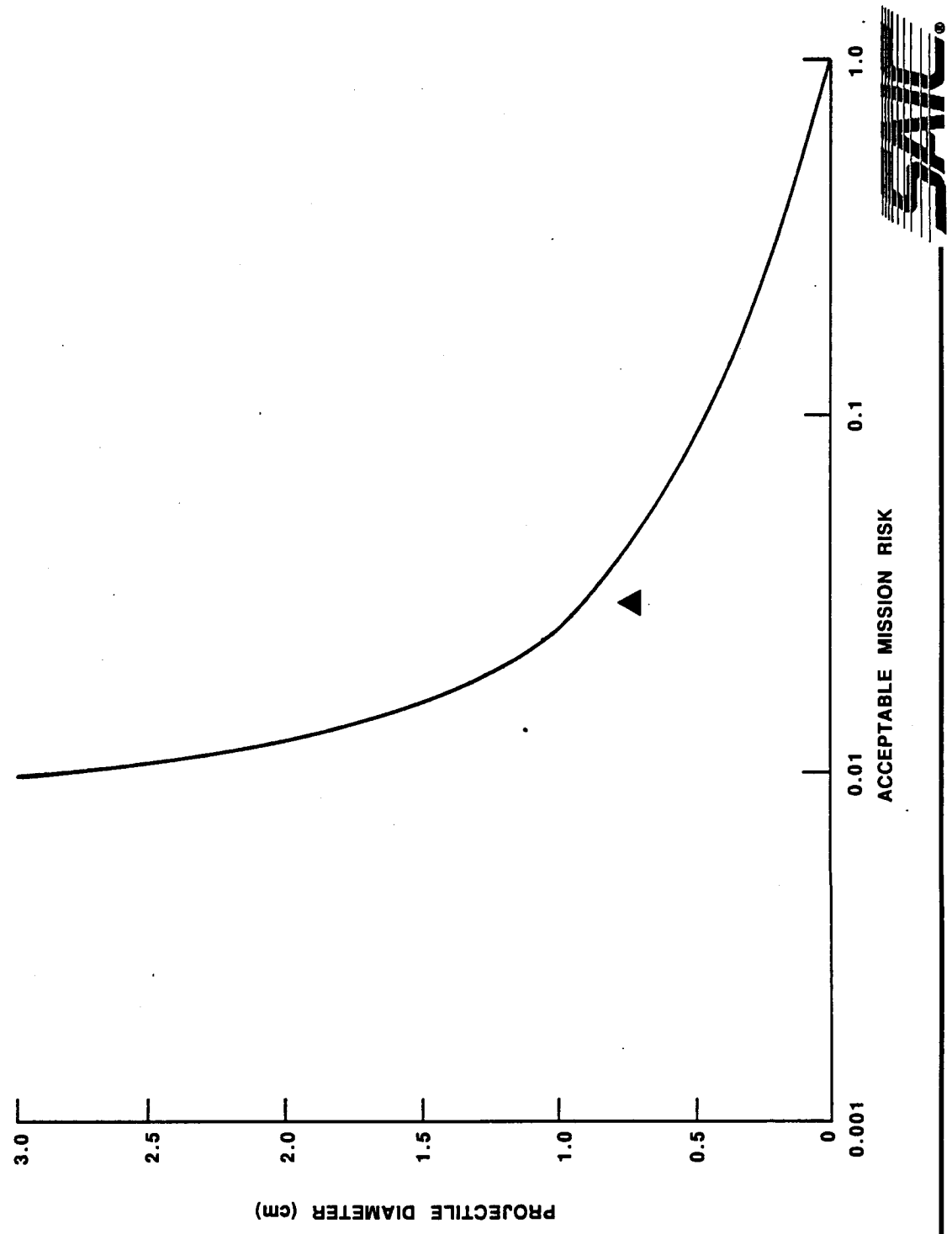
## **EFFECT OF MISSION RISK ON PROJECTILE DIAMETER**

**THE EFFECT OF MISSION RISK ON PROJECTILE  
DIAMETER IS SHOWN FOR THE DEBRIS  
SCENARIO. NOTE THAT AN INCREASE IN  
PROBABILITY OF NO PENETRATION FROM  
THE BASELINE INDUCES A LARGE INCREASE  
IN REQUIRED DESIGN.**

BM12-8/21

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# EFFECT OF MISSION RISK ON PROJECTILE DIAMETER



**SIGNIFICANT DESIGN PENALTY INDUCED BY INCREASE IN  
PROBABILITY OF NO PENETRATION: BOEING PREDICTOR**

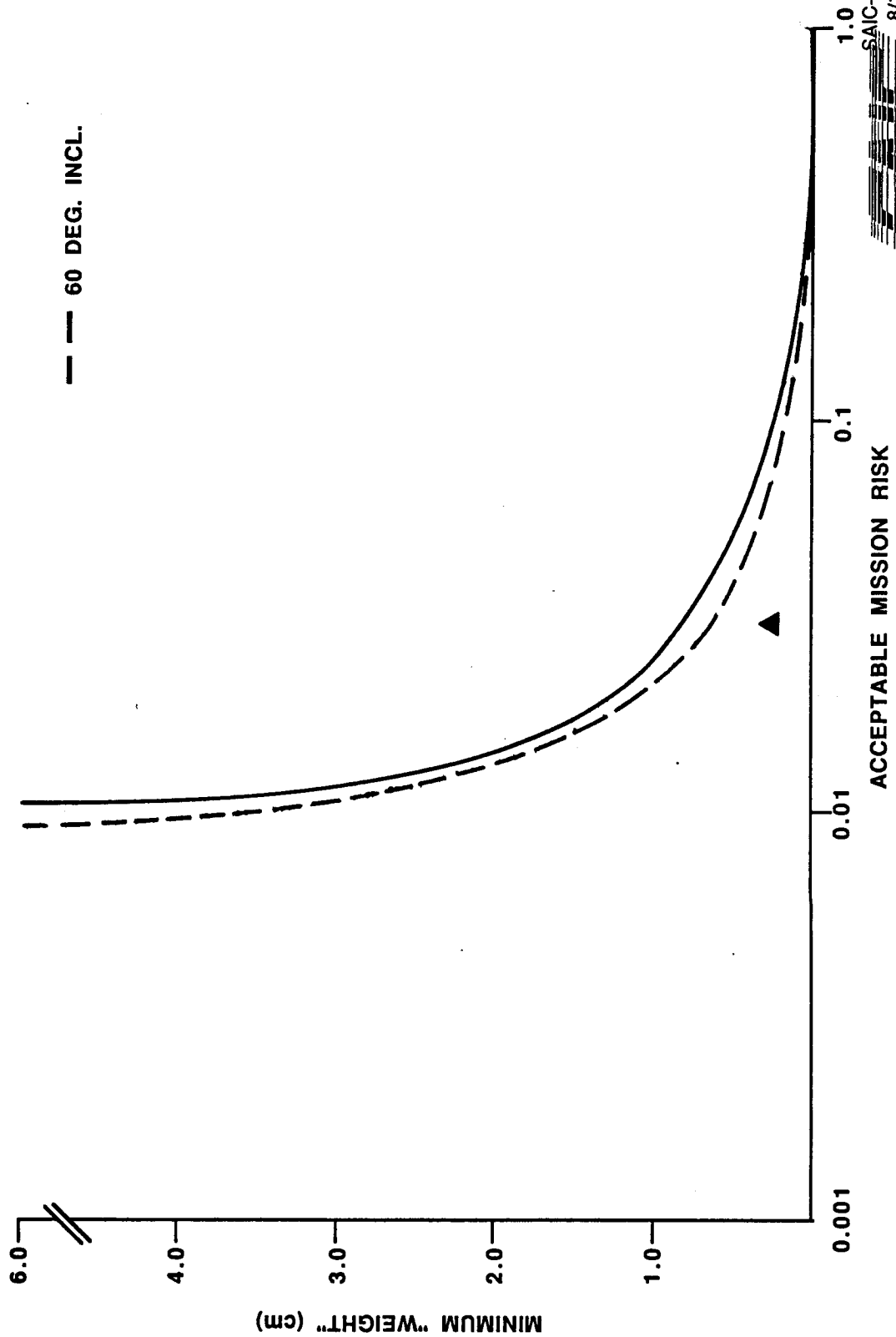
**SHOWN IS THE EFFECT OF ACCEPTABLE MISSION RISK ON OPTIMAL  
DESIGN FOR THE BOEING PREDICTOR FOR 30 AND 60 DEGREE INCLI-  
NATIONS. NOTE THE DRASTIC INCREASE IN OPTIMAL DESIGN FOR  
PROBABILITY OF NO PENETRATION ABOVE 0.97.**

BM04-8/11

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# SIGNIFICANT DESIGN PENALTY INDUCED BY INCREASE IN PROBABILITY OF NO PENETRATION: BOEING PREDICTOR



SAIC-664H  
8/11/87

**SAIC.**

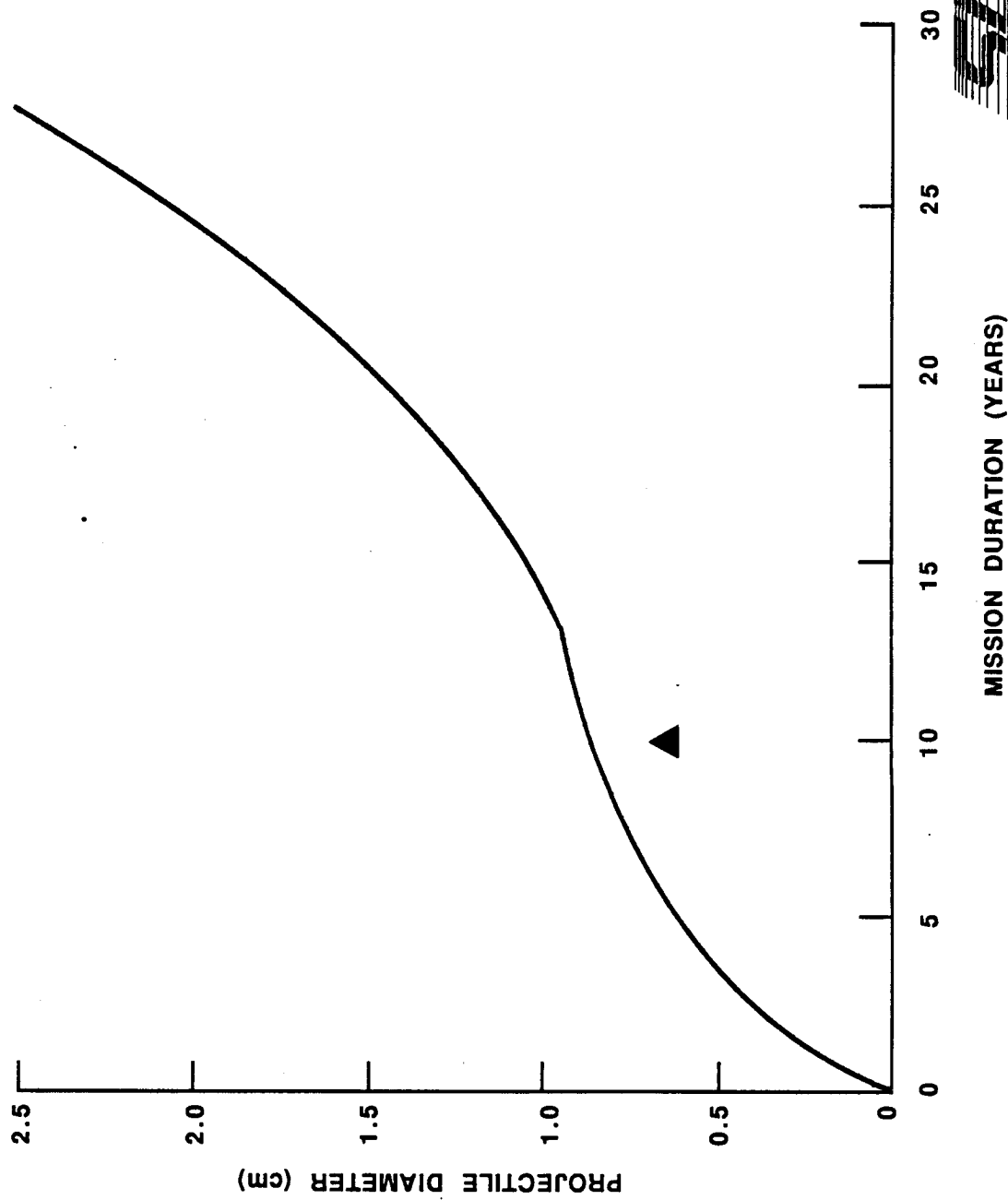
## **EFFECT OF MISSION DURATION ON PROJECTILE DIAMETER**

**THE EFFECT OF MISSION DURATION ON  
PROJECTILE DIAMETER IS SHOWN FOR THE  
DEBRIS SCENARIO. NOTE THE INFLECTION  
AT ABOUT 15 YEARS. THIS CORRESPONDS  
TO THE INFLECTION IN THE DEBRIS  
ENVIRONMENT CURVE AT A PROJECTILE  
DIAMETER OF 1 CM.**

BM13-8/21

**SAIC**<sup>®</sup>

# EFFECT OF MISSION DURATION ON PROJECTILE DIAMETER



**SAIL.**

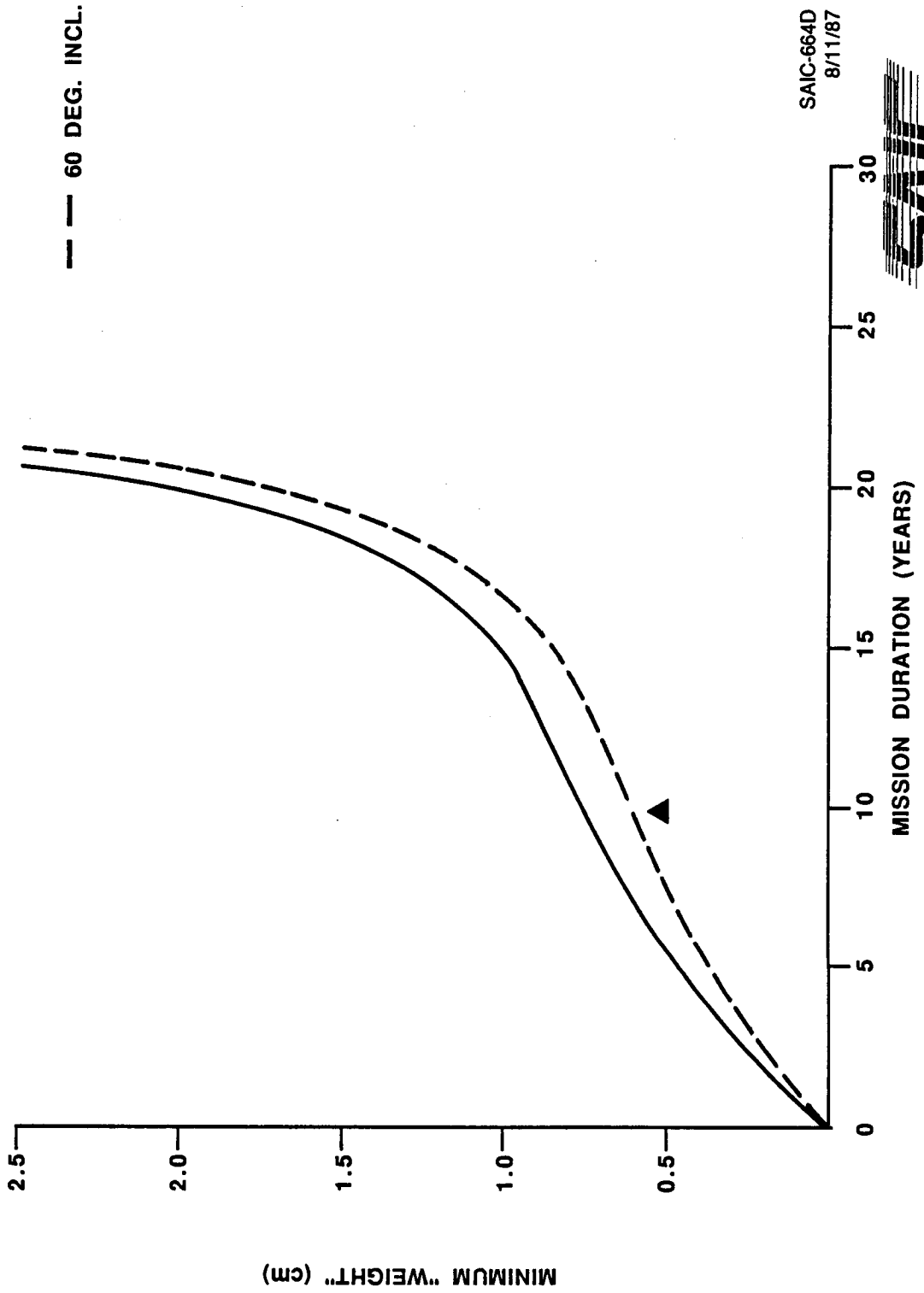
## **SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION MISSIONS: BOEING PREDICTOR**

**SHOWN IS THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR  
THE BOEING PREDICTOR FOR 30 AND 60 DEGREE INCLINATIONS. THE  
INFLECTION AT 15 YEARS, AND THE SHARP INCREASE IN SLOPE AT  
ABOUT 22 YEARS RAISES SERIOUS DESIGN QUESTIONS ABOUT LONG-  
DURATION MISSIONS FOR MISSION PLANNERS.**

BM05-8/11



**SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION  
MISSIONS: BOEING PREDICTOR**



SAIC-664D  
8/11/87



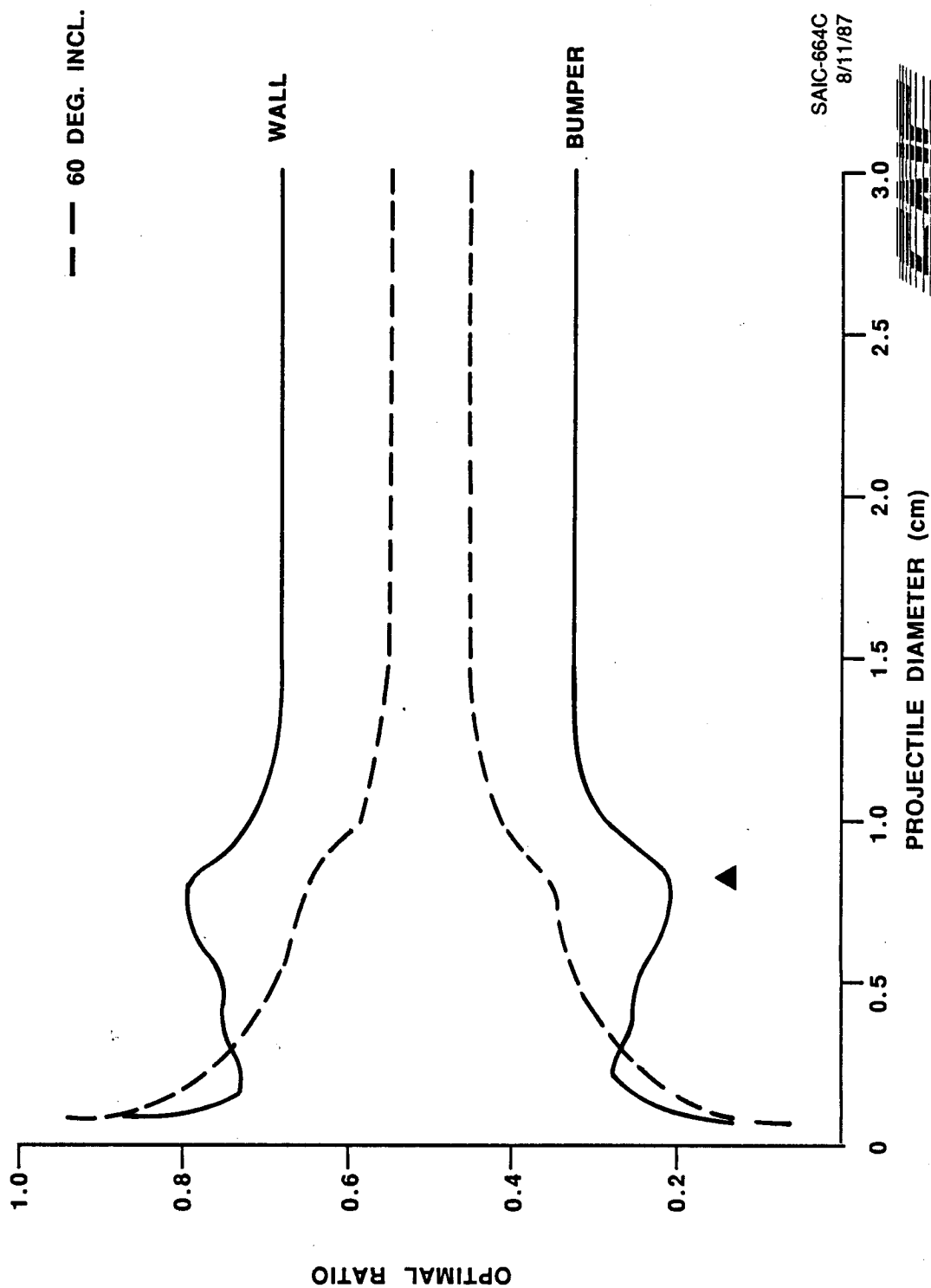
## **GP PROVIDES OPTIMAL DISTRIBUTION FOR BOEING PREDICTOR**

**THE OPTIMAL RATIO AS A FUNCTION OF PROJECTILE DIAMETER FOR THE BOEING PREDICTOR IS SHOWN FOR 30 AND 60 DEGREE INCLINATIONS. THIS IS THE RATIO OF OPTIMAL BUMPER (WALL) THICKNESS TO TOTAL OPTIMAL THICKNESS, AND IS QUITE NONLINEAR (AND NONCONSTANT). THIS NONLINEARITY HAS TO DO WITH THE INTERACTION OF THE MODIFIED BURCH AND WILKINSON PREDICTORS. NOTE THAT A 60 DEGREE INCLINATION TENDS TO EVEN OUT THE THICKNESS DISTRIBUTION BETWEEN BUMPER AND WALL, EXCEPT FOR SMALL PARTICLE DIAMETERS.**

BM06-8/11

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# GP PROVIDES OPTIMAL DISTRIBUTION FOR BOEING PREDICTOR



SAIC-664C  
8/11/87



## DESIGNER'S COST EXCURSION

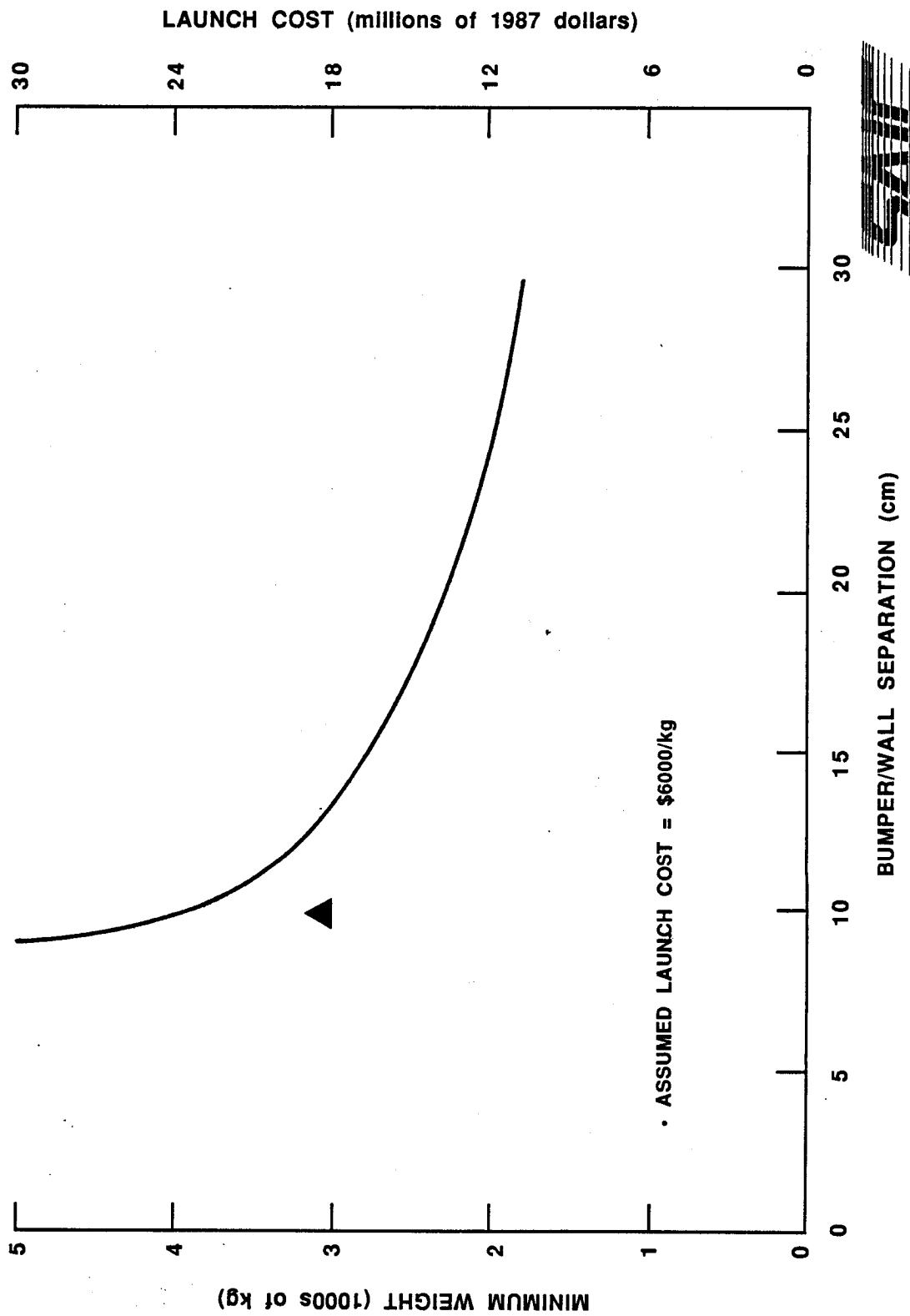
SHOWN IS THE EFFECT OF BUMPER/WALL SEPARATION ON CORE MODULE CONFIGURATION WEIGHT AND LAUNCH COST FOR THE BOEING PREDICTOR. THE ASSUMED LAUNCH COST IS \$6000/KG. BASED ON THIS ASSUMPTION, A SAVINGS OF ROUGHLY \$7M (30%) IN LAUNCH COST IS INDUCED BY AN INCREASE IN SEPARATION FROM 10 TO 15 CM.

BM19-8/21

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# DESIGNER'S COST EXCURSION



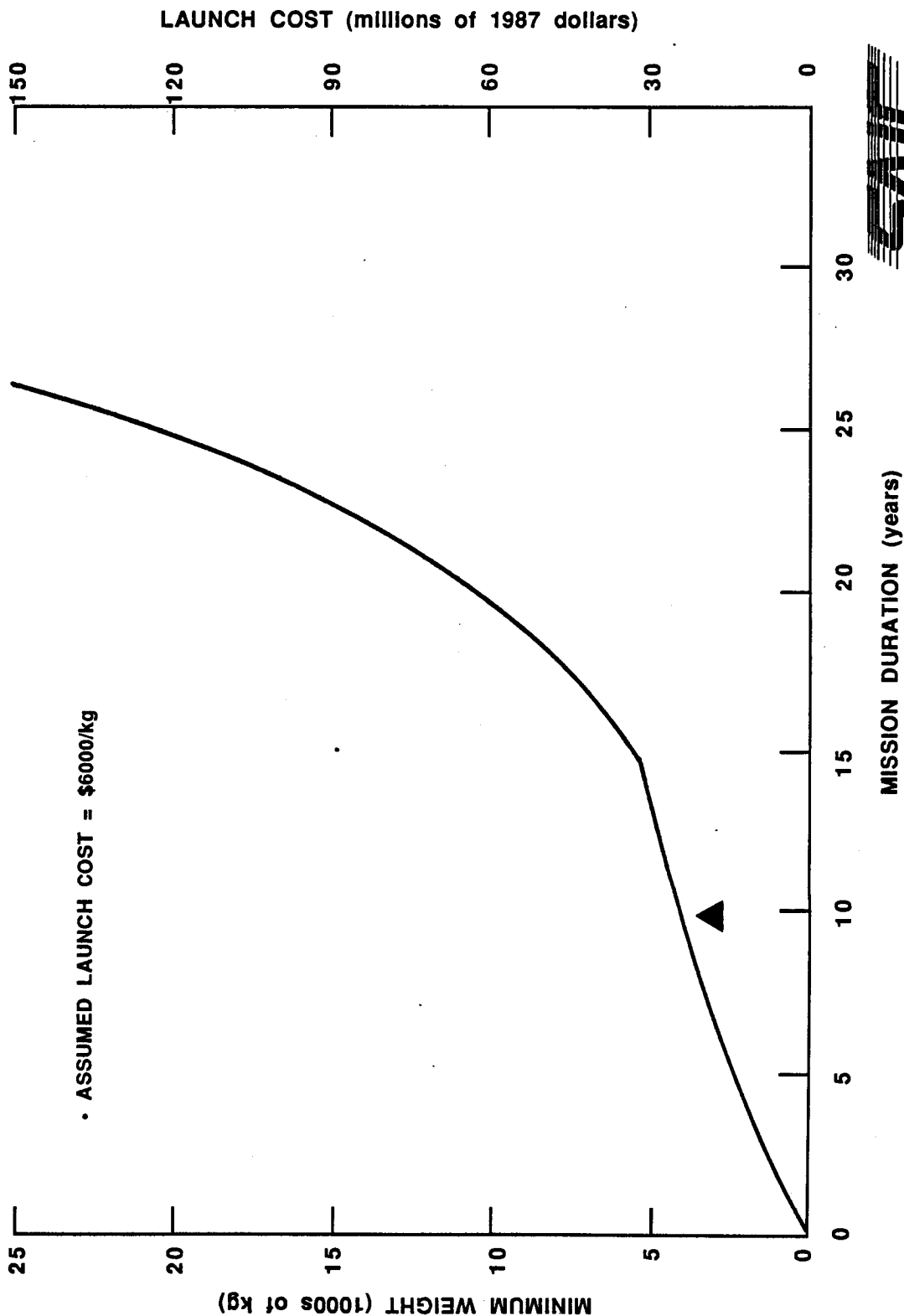
## MISSION PLANNER'S COST EXCURSION

THE EFFECT OF MISSION DURATION ON CORE MODULE CONFIGURATION WEIGHT AND LAUNCH COST IS SHOWN FOR THE BOEING PREDICTOR. THE ASSUMED LAUNCH COST IS \$6000/KG. BASED ON THIS ASSUMPTION, AN INCREASE IN LAUNCH COST OF \$37M (163%) IS INDUCED BY INCREASING THE MISSION DURATION FROM 10 TO 20 YEARS.

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# MISSION PLANNER'S COST EXCURSION



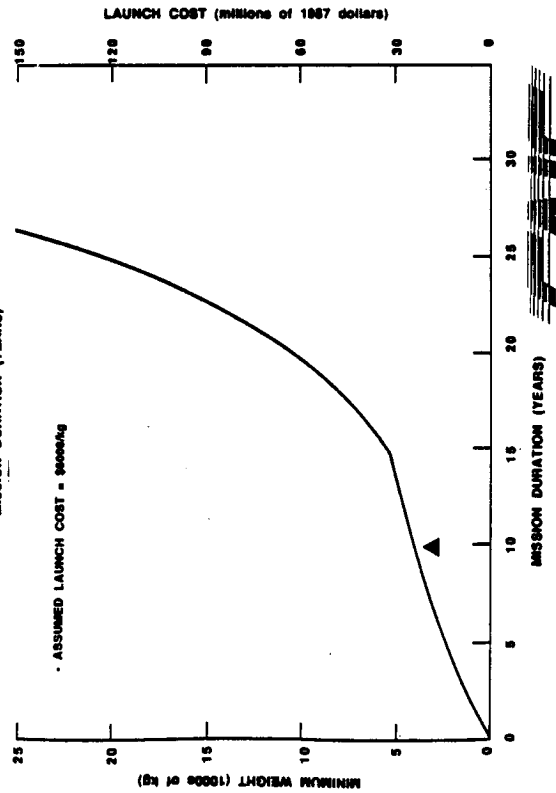
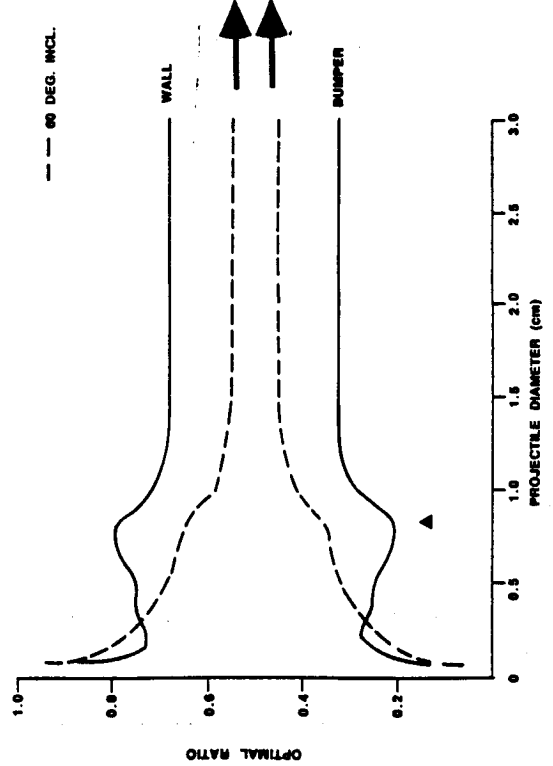
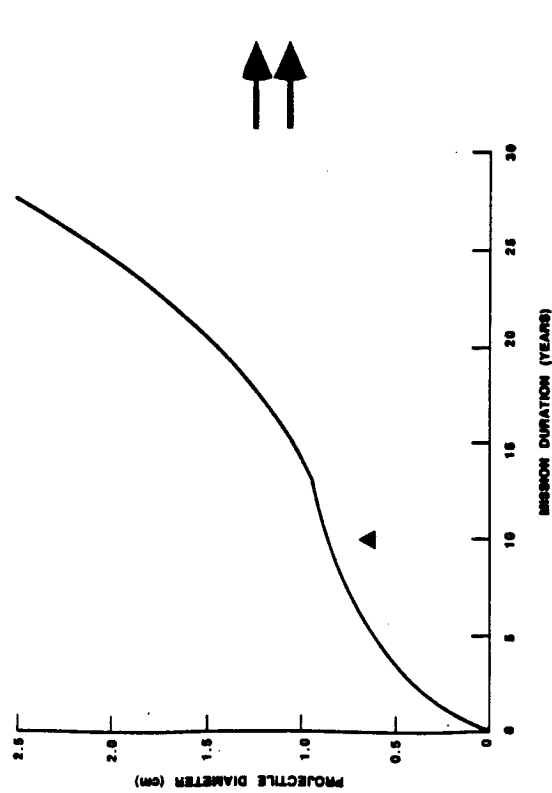
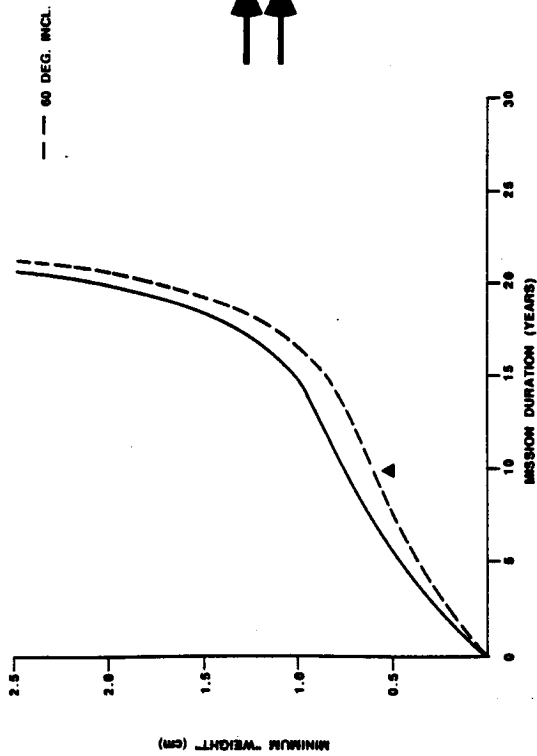
## DETERMINING THE OPTIMAL PARAMETERS

AN EXAMPLE FOR DETERMINING THE OPTIMAL DESIGN PARAMETERS FOR THE VELOCITY-INTEGRATED BOEING PREDICTOR IS SHOWN. STARTING IN THE UPPER LEFT-HAND CORNER, IT IS DETERMINED THAT THE SUM OF THE MINIMUM BUMPER AND WALL THICKNESSES FOR A 10-YEAR MISSION (AND 30 DEGREE ORBITAL) INCLINATION IS ROUGHLY 0.75 CM. PROCEEDING TO THE RIGHT, ONE DETERMINES THE CRITICAL PROJECTILE DIAMETER TO BE APPROXIMATELY 0.85 CM. THIS CORRESPONDS TO AN OPTIMAL DISTRIBUTION OF 20% BUMPER, 80% WALL IN THE LOWER LEFT-HAND CORNER. THUS, THE OPTIMAL DESIGN THICKNESSES ARE DETERMINED TO BE ROUGHLY 0.15 CM FOR THE BUMPER, AND 0.60 CM FOR THE WALL. FINALLY, THE ACTUAL WEIGHT OF APPROXIMATELY 4000Kg AND COST OF ROUGHLY \$24M ARE DETERMINED FROM THE LOWER RIGHT-HAND CHART.

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# DETERMINING THE OPTIMAL PARAMETERS



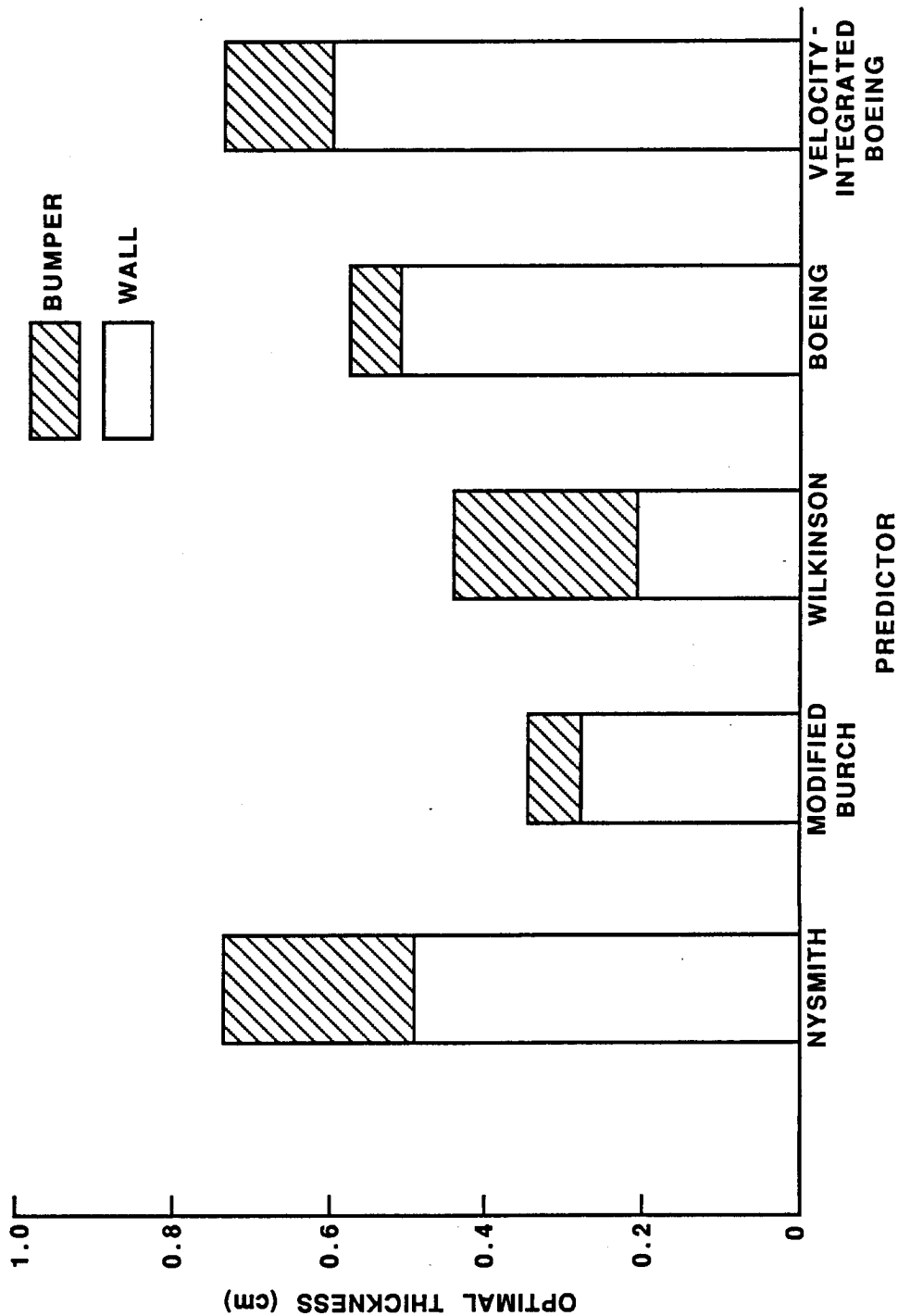
## SUMMARY OF PREDICTOR RESULTS

SHOWN ARE THE OPTIMAL THICKNESSES FOR THE BASELINE PARAMETERS FOR EACH OF THE FIVE PREDICTORS INVESTIGATED IN THIS STUDY. IT IS INTERESTING TO NOTE THE DIVERSITY OF TOTAL THICKNESSES AND THICKNESS DISTRIBUTIONS FOR THESE CASES. NOTE ALSO THAT THE NYSMITH AND VELOCITY-INTEGRATED BOEING PREDICTORS BOTH ACHIEVE THE SAME TOTAL THICKNESSES, ALTHOUGH IN DIFFERENT PROPORTIONS.

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# SUMMARY OF PREDICTOR RESULTS



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## SECTION VII CONCLUSIONS

### GEOMETRIC PROGRAMMING CONCLUSIONS

- GEOMETRIC PROGRAMMING (GP) IS SUPERIOR TO THE EXTREMA THEOREM (ET) FOR THOSE IMPACT PROBLEMS WHERE BOTH METHODS ARE APPLICABLE
- THIS SUPERIORITY INCREASES WITH INCREASING DESIGN COMPLEXITY
- REDUCTION OF THE GEOMETRIC PROGRAMMING PROBLEM FROM 5 DEGREES-OF-DIFFICULTY TO 2 RESULTS IN NEGLIGIBLE DESIGN ERROR (PROVIDED BUMPER AND WALL THICKNESSES REMAIN SMALL IN COMPARISON TO MODULE RADIUS)
- OPTIMAL DESIGN DETERMINED FROM SPECIFIC MODULE CONFIGURATION IS NO DIFFERENT THAN FROM IDEALIZED SCENARIO.
- GEOMETRIC PROGRAMMING APPLIES TO NONLINEAR, FUNCTIONAL, PIECE-WISE CONTINUOUS (E.G., WILKINSON) PREDICTORS IN POSYNOMIAL FORM
- SINCE IMPACT PREDICTOR INDEPENDENT VARIABLES ARE INHERENTLY POSITIVE-VALUED, THE ONLY POTENTIAL DOWNFALL FOR GEOMETRIC PROGRAMMING IS NEGATIVE COEFFICIENTS.
- THE BURCH PREDICTOR IS EASILY MODIFIED TO SATISFY THE POSYNOMIAL REQUIREMENT
- THE PEN4 PREDICTOR MAY NOT BE EASILY MODIFIED TO SATISFY THE POSYNOMIAL REQUIREMENT.

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## SECTION VII CONCLUSIONS (CONT'D)

### NYSMITH PREDICTOR CONCLUSIONS

- THE NYSMITH PREDICTOR HAS A THIRD INEQUALITY CONSTRAINT WHICH LIMITS ITS USAGE.
- THE COMPUTER SOLUTION REGION FOR THE NYSMITH PREDICTOR IS NARROW ENOUGH (FOR MOST PROBLEMS) TO BE APPROXIMATED ANALYTICALLY.
- THE NYSMITH PREDICTOR IMPLIES AN OPTIMAL THICKNESS DISTRIBUTION OF 35% BUMPER AND 65% WALL.
- THE NYSMITH PREDICTOR REQUIRES OPTIMAL BALLISTIC LIMIT THICKNESSES ROUGHLY 1.5 TIMES CURRENT DESIGN (FOR THE BASELINE DESIGN PARAMETERS)
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN FOR THE CORE MODULE CONFIGURATION.
- INCREASING THE BASELINE  $P_0$  HEAVILY TAXES THE DESIGN.
- A 50% INCREASE IN THE BASELINE BUMPER/WALL SEPARATION PROVIDES A 30% DECREASE IN THE TOTAL DESIGN THICKNESS.
- THE NYSMITH PREDICTOR SHOWS LITTLE DESIGN SENSITIVITY TO PROJECTILE VELOCITY.
- DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION.

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## **SECTION VII CONCLUSIONS (CONT'D)**

### **BOEING SUBPREDICTOR CONCLUSIONS**

- THE PEN4 PREDICTOR SHOWS NO DEPENDENCY ON BUMPER/WALL SEPARATION
- THE PEN4 PREDICTOR IS NOT VALID FOR VELOCITIES ABOVE ROUGHLY 2.8 KM/SEC.
- ONE LOCAL OPTIMAL DESIGN DISTRIBUTION FOR THE PEN4 PREDICTOR IS 100% BUMPER, 0% WALL
- THE BURCH PREDICTOR SHOWS NO DEPENDENCY ON PROJECTILE OR WALL MATERIAL PROPERTIES
- THE MODIFIED BURCH PREDICTOR APPROXIMATES THE BURCH MODEL WELL
- THE MODIFIED BURCH MINIMUM "WEIGHT" IS INVERSELY PROPORTIONAL TO PROJECTILE VELOCITY
- THE WILKINSON PREDICTOR IS A PIECEWISE CONTINUOUS MODEL
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN FOR THE MODIFIED BURCH AND WILKINSON PREDICTORS
- THE WILKINSON PREDICTOR SHOWS MORE SENSITIVITY TO BUMPER/WALL SEPARATION, PROJECTILE DIAMETER, MISSION RISK, AND MISSION DURATION THAN THE MODIFIED BURCH PREDICTOR
- OPTIMAL RATIOS ARE FAIRLY CONSTANT FOR ALL 3 BOEING SUBPREDICTORS

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## **SECTION VII CONCLUSIONS (CONT'D)**

### **BOEING PREDICTOR CONCLUSIONS**

- THE BOEING PREDICTOR IS A COMPLEX PIECEWISE CONTINUOUS PREDICTOR
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES THE DESIGN FOR THE BOEING PREDICTOR
- THE OPTIMAL DESIGN AS A FUNCTION OF PROJECTILE VELOCITY IS NOT MONOTONIC
- THE BOEING PREDICTOR SHOWS SHARP SENSITIVITIES TO BUMPER/WALL SEPARATION, PROJECTILE DIAMETER, ACCEPTABLE MISSION RISK AND DURATION
- THE OPTIMAL RATIO FOR THE BOEING PREDICTOR IS ALSO NOT MONOTONIC AND IS FAIRLY SENSITIVE TO SMALL PROJECTILE DIAMETERS

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## SECTION VII CONCLUSIONS (CONT'D)

### VELOCITY-INTEGRATED BOEING PREDICTOR CONCLUSIONS

- UNDER THESE ASSUMPTIONS, A 60 DEGREE ORBITAL INCLINATION IS PREFERABLE TO A 30 DEGREE ONE FOR THE BOEING PREDICTOR
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN
- THIS PREDICTOR SHOWS STRONG SENSITIVITIES TO BUMPER/WALL SEPARATION, PROJECTILE DIAMETER, ACCEPTABLE MISSION RISK, AND DURATION
- THE OPTIMAL RATIO FOR THE VELOCITY-INTEGRATED PREDICTOR IS MONOTONIC FOR A 60 DEGREE ORBITAL INCLINATION, BUT NOT FOR A 30 DEGREE ONE

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## SECTION VIII RECOMMENDATIONS

- EVALUATION OF BURCH, BOEING, AND VELOCITY-INTEGRATED BOEING PREDICTORS FOR NON-NORMAL IMPACTS
- COMPARISON OF RESULTS WITH BOEING'S BUMPER CODE
- FULL DESIGN TRADE EVALUATIONS FOR MADDEN, RICHARDSON, AND OTHER AVAILABLE PREDICTORS
- PREDICTOR/TEST DATA CORRELATION
- DESIGN GENERALIZATION TO INCLUDE CONSTRAINTS RELATED TO PRESSURE, THERMAL, STRESS, RADIATION, CONTAMINATION, AND OTHER EFFECTS AS APPLICABLE
- APPLICATION OF THIS DESIGN METHODOLOGY TO SPACE STATION COMPONENTS OTHER THAN CORE MODULE CONFIGURATION (E.G., TANKS, OMV, OTV)
- APPLICATION OF THIS DESIGN METHODOLOGY TO OTHER PROGRAMS (E.G., DEEP SPACE PROBES, PLANETARY MISSIONS, TRANSFER VEHICLES, SPACEPORTS)

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## **SECTION VIII RECOMMENDATIONS (CONT'D)**

- **COMPUTER CODE DEVELOPMENT TO ANALYZE GENERIC PREDICTORS**
- **EVALUATION OF EFFECT OF EVOLVING SPACE DEBRIS ENVIRONMENT ON DESIGN**
- **EVALUATION OF EFFECT OF CHANGES IN CMC DESIGN ON OPTIMAL THICKNESSES**
- **COMPUTER PLOTTING POST-PROCESSOR FOR RAPID DISPLAY OF DESIGNER TRADEOFFS**

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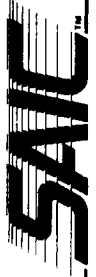
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# SECTION IX

## REFERENCES

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## **SURVIVABILITY AND PREDICTOR REFERENCES**

1. SUSKO, M., "A REVIEW OF MICROMETEORID FLUX MEASUREMENTS AND MODELS FOR LOW ORBITAL ALTITUDES OF THE SPACE STATION", NASA TM-86466, GEORGE C. MARSHALL SPACE FLIGHT CENTER, SEPTEMBER 1984.
2. KESSLER, D., "ORBITAL DEBRIS ENVIRONMENT FOR SPACE STATION," JSC-20001.
3. NYSMITH, C.R., "AN EXPERIMENTAL IMPACT INVESTIGATION OF ALUMINUM DOUBLE-SHEET STRUCTURES", AIAA HYPERVELOCITY IMPACT CONFERENCE, CINCINNATI, OHIO, APRIL 30-MAY 2, 1969, AIAA PAPER NO. 69-375.

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**SURVIVABILITY AND PREDICTOR REFERENCES  
(CONTINUED)**

4. WILKINSON, J.P.D., "A PENETRATION CRITERION FOR DOUBLE-WALLED STRUCTURES SUBJECT TO METEOROID IMPACT," AIAA JOURNAL, VOL. 7, NO. 10, OCTOBER, 1969.
5. CORONADO, A.R., GIBBINS, M.N., WRIGHT, M.A., AND STERN, P.H., "SPACE STATION INTEGRATED WALL DESIGN AND PENETRATION DAMAGE CONTROL," BOEING AEROSPACE COMPANY FINAL REPORT, CONTRACT NAS8-36426, JULY 1987.
6. COUR-PALAIS, B., "METEOROID ENVIRONMENT MODEL - 1969 (NEAR-EARTH TO LUNAR SURFACE)", NASA SP-8013, MARCH 1969.

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## OPTIMIZATION REFERENCES

1. GOTTFRIED, B.S., AND WEISMAN, J., INTRODUCTION TO OPTIMIZATION THEORY, PRENTICE-HALL, INC., ENGLEWOOD CLIFFS, NEW JERSEY, 1973.
2. AVRIEL, M., ADVANCES IN GEOMETRIC PROGRAMMING, PLENUM PRESS, NEW YORK, 1980.
3. WHITTLE, P., OPTIMIZATION UNDER CONSTRAINTS, JOHN WILEY & SONS, LTD., 1971.
4. WILDE, D.J., GLOBALLY OPTIMAL DESIGN, JOHN WILEY & SONS, INC., 1978.
5. AVRIEL, M., NONLINEAR PROGRAMMING ANALYSIS AND METHODS, PRENTICE-HALL, INC., ENGLEWOOD CLIFFS, NEW JERSEY, 1976.

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OPTIMIZATION REFERENCES  
(CONTINUED)

6. MCCORMICK, G.P., NONLINEAR PROGRAMMING THEORY, ALGORITHMS, AND APPLICATIONS, JOHN WILEY & SONS, INC., 1983.
7. VANDERPLAATS, G.N., NUMERICAL OPTIMIZATION TECHNIQUES FOR ENGINEERING DESIGN WITH APPLICATIONS, MCGRAW-HILL, INC., 1984.
8. PRICE, D. MARVIN, UNPUBLISHED MASTER'S THESIS AND TECHNICAL DOCUMENTATION ON THE SUBJECT OF GEOMETRIC PROGRAMMING.

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# SECTION X

## APPENDICES

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# A. MATHEMATICS

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### GP APPLIED TO NYSMITH

Consider the Nysmith Equation:

$$t_2 = 5.08V^{.278}d^{2.92}/(t_1^{.528}h^{1.39}) ,$$

with inequality constraints

$$t_1/d \leq 0.5 , t_2/d \leq 1.0$$

Note that if

$$d > 0.24hV^{-0.2} , \text{ then}$$

$$\frac{t_1}{d} \leq 0.5 \Rightarrow$$

$$\frac{t_2}{d} > 5.08V^{.278}(0.24hV^{-0.2})^{1.39}/[(0.5)^{.528}h^{1.39}] \text{ or ,}$$

$$\frac{t_2}{d} > 1.0$$

Therefore, the third inequality constraint of Nysmith may be written:

$$d \leq 0.24hV^{-0.2}$$

Letting the idealized "weight" be denoted by  $w$  , one has:

$$w = t_1 + t_2$$

Substituting Nysmith, one has:

$$w = t_1 + 5.08V^{.278}d^{2.92}/(t_1^{.528}h^{1.39}) ,$$

with inequality constraints:

$$\frac{2t_1}{d} \leq 1.0 , 5.08V^{.278}d^{1.92}/(t_1^{.528}h^{1.39}) \leq 1.0$$

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## A. Unconstrained Optimization

The dual GP problem may be written:

$$\text{maximize:} \quad v(\delta) = (1/\delta_1)^{\delta_1} (c_1/\delta_2)^{\delta_2}$$

$$\text{subject to:} \quad \delta_1 + \delta_2 = 1$$

$$\delta_1 - 0.528\delta_2 = 0$$

$$\text{where:} \quad c_1 = 5.08V^{-278}d^{2.92}/h^{1.39}$$

This is easily solved, giving:

$$\delta_1 = 0.35, \quad \delta_2 = 0.65,$$

$$w_0 = 5.52V^{.18}d^{1.91}/h^{0.91}$$

is the minimum "weight".

$$t_{1_0} = 1.93V^{.18}d^{1.91}/h^{0.91}$$

is the optimal bumper thickness, and

$$t_{2_0} = 3.59V^{.18}d^{1.91}/h^{0.91}$$

is the optimal wall thickness.

Note that the optimal ratios are given by:

$$\frac{t_{1_0}}{t_{1_0} + t_{2_0}} = 0.35 = \delta_1, \quad \frac{t_{2_0}}{t_{1_0} + t_{2_0}} = 0.65 = \delta_2$$

Furthermore, this analytic solution is valid for

$$d \leq 0.23hV^{-0.2} \quad \text{Why?}$$

$$h \geq 4.35dV^{0.2} \Rightarrow t_{1_0} \leq 1.93V^{.18}d^{1.91}(4.35dV^{0.2})^{-0.91} \quad \text{or}$$

$$t_{1_0} \leq 0.5d, \quad \text{as desired. Also,}$$

$$t_{2_0} = 1.86t_{1_0} < d, \quad \text{as required.}$$

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Thus the constrained problem need only be solved for

$$0.23hV^{-0.2} \leq d \leq 0.24hV^{-0.2}$$

### B. Constrained Optimization

The constrained dual GP problem may be written:

maximize:  $v(\delta) = (1/\delta_1)^{\delta_1} (c_1/\delta_2)^{\delta_2} (c_3)^{\delta_{11}'} (c_4)^{\delta_{12}'}$

subject to:  $\delta_1 + \delta_2 = 1$

$$\delta_1 - 0.528\delta_2 + \delta_{11}' - 0.528\delta_{12}' = 0$$

where:  $c_1$  is defined as in part A

$$c_2 = c_1/d$$

$$c_3 = 2/d$$

This is a 2 degree-of-difficulty problem, since there are 2 equations and 4 unknowns. It is solved numerically.

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### DERIVATION OF CORE MODULE CONFIGURATION WEIGHT

Let:  $r_{12}$  = radius of a core module

$$r_{22} = r_{12} + t_2$$

$$r_{11} = r_{22} + h$$

$$r_{21} = r_{11} + t_1$$

$L$  = core module length

Then,

$$w = \pi L [\rho_1(r_{21}^2 - r_{11}^2) + \rho_2(r_{22}^2 - r_{12}^2)]$$

is the total core module weight.

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### GP APPLIED TO THE CMC WEIGHT FUNCTION

Let:  $r_{12} = 210.8 \text{ cm}$

$L = 1356.7 \text{ cm}$

$\rho_1 = \rho_2 = 2.81 \text{ gm/cm}^3$

Applying the Nysmith equation, one has:

$$w_{CMC} = 12t_1^2 + c_1t_1 + 122c_2t_1^{0.472} + 25700c_2t_1^{-0.528} + 310c_2^2t_1^{-1.06}$$

where:

$c_1 = 5059 + 24h$  , and

$c_2 = V^{278}d^{2.92}/h^{1.39}$

The chosen approximate weight is given by:

$$w_{CMC_{Approx}} = c_1t_1 + 25700c_2t_1^{-0.528}$$

The unconstrained GP problem is then:

$$\text{maximize: } v(\delta) = (c_1/\delta_1)^{\delta_1} \left( \frac{25700c_2}{\delta_2} \right)^{\delta_2}$$

$$\text{subject to: } \delta_1 + \delta_2 = 1$$

$$\delta_1 - .528\delta_2 = 0$$

This is easily solved yielding:

$$\delta_1 = 0.346 \text{ , } \delta_2 = 0.654$$

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$$w_0 = 1459 c_1^{0.346} c_2^{0.654}$$

$$t_{1_0} = \frac{\delta_1 w_0}{c_1} = 505 \left( \frac{c_2}{c_1} \right)^{0.654}$$

$$t_{2_0} = 1.89 t_{1_0} = 954 \left( \frac{c_2}{c_1} \right)^{0.654}$$

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## GP APPLIED TO WILKINSON

Recall that:

$$\frac{D\rho_p}{\rho_1 t_1} \leq 1 \Rightarrow t_2 = 0.364 D^3 \rho_p V_N / (L_2 S^2 \rho_2) \text{ and ,}$$

$$\frac{D\rho_p}{\rho_1 t_1} > 1 \Rightarrow t_2 = 0.364 D^4 \rho_p^2 V_N / (L_2 S^2 \rho_1 t_1 \rho_2)$$

Consider the case where:

$$\frac{D\rho_p}{\rho_1 t_1} > 1$$

Then,  $w = t_1 + c_1 t_1^{-1}$  is the idealized weight.

Where:

$$c_1 = 0.364 D^4 \rho_p^2 V_N / (L_2 S^2 \rho_1 \rho_2)$$

The dual GP problem may be written:

$$\text{maximize:} \quad v(\delta) = (1/\delta_1)^{\delta_1} (c_1/\delta_2)^{\delta_2}$$

$$\text{subject to:} \quad \delta_1 + \delta_2 = 1$$

$$\delta_1 - \delta_2 = 0$$

Thus,  $\delta_1 = \delta_2 = 1/2$  , and

$$w_0 = 1.207 \frac{D^2 \rho_p}{S} \left( \frac{V_N}{L_2 \rho_1 \rho_2} \right)^{1/2}$$

$$t_{1_0} = t_{2_0} = 0.604 \frac{D^2 \rho_p}{S} \left( \frac{V_N}{L_2 \rho_1 \rho_2} \right)^{1/2}$$

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Thus, the procedure is the following:

- 1) Determine  $t_{1_0}$  ,  $t_{2_0}$  from the above equation.
- 2) Compute  $\frac{D \rho_p}{\rho_1 t_{1_0}}$  .
- 3) If  $\frac{D \rho_p}{\rho_1 t_{1_0}} > 1$  , then quit. Optimal design is  $(t_{1_0}, t_{2_0})$  .
- 4) If  $\frac{D \rho_p}{\rho_1 t_{1_0}} \leq 1$  , optimal design is  $\left( t_{1_0}, t_{2_0} \left( \frac{D \rho_p}{\rho_1 t_{1_0}} \right) \right)$  .

### Optimal Ratios for Wilkinson

Recall that the optimal thickness distribution between bumper and wall is equal unless:

$$\frac{D \rho_p}{\rho_1 t_{1_0}} \leq 1 \quad , \text{ or } \quad t_{1_0} \geq \frac{D \rho_p}{\rho_1} \quad .$$

This implies:

$$0.604 \frac{D^2 \rho_p}{S} \left( \frac{V_N}{L_2 \rho_1 \rho_2} \right)^{1/2} \geq \frac{D \rho_p}{\rho_1} \quad , \text{ or }$$

$$D \geq 1.66s \left( \frac{L_2 \rho_2}{V_N \rho_1} \right)^{1/2}$$

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## GP APPLIED TO MODIFIED BURCH

Recall the Modified Burch Predictor:

$t_2 = \bar{C} \bar{K}$  , where

$$\bar{C} = \left(\frac{D}{N}\right)^{1.71} \left(\frac{C}{V}\right)^{2.29} / S^{0.71} , \text{ and}$$

$$\bar{K} = 2.8(t_1/D)^{0.57} + 1.58(t_1/D)^{-0.57}$$

Thus,

$w = t_1 + 2.8\bar{C}D^{-0.57}t_1^{0.57} + 1.58\bar{C}D^{0.57}t_1^{-0.57}$  is the idealized weight.

Thus, the GP dual problem may be written:

$$\text{Maximize:} \quad v(\delta) = \left(\frac{1}{\delta_1}\right)^{\delta_1} \left(\frac{2.8\bar{C}D^{-0.57}}{\delta_2}\right)^{\delta_2} \left(\frac{1.58\bar{C}D^{0.57}}{\delta_3}\right)^{\delta_3}$$

$$\text{Subject to:} \quad \delta_1 + 0.57\delta_2 - 0.57\delta_3 = 0 , \text{ and}$$

$$\delta_1 + \delta_2 + \delta_3 = 1$$

Thus, we have:

$$\delta_2 = 2.33(1 - 1.57\delta_3) , \quad \delta_1 = 1.33(2\delta_3 - 1) ,$$

and since  $\delta_1 > 0$  ,  $\delta_2 > 0$  , we have  $0.5 < \delta_3 < 0.64$  .

This is a one degree-of-difficulty problem with the following procedure:

- 1) Vary  $\delta_3$  from 0.5 to 0.64 to find the max  $v(\delta)$  .
- 2) Using the corresponding  $\delta_3$  , solve for  $\delta_1$  ,  $\delta_2$  .
- 3) Let  $t_{1_0} = \delta_1(\max(v(\delta)))$  .
- 4) Let  $t_{2_0} = \max(v(\delta)) - t_{1_0}$  .

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### OPTIMAL DESIGN ALGORITHM FOR BOEING PREDICTOR

1. Compute optimal design for PEN4 Predictor,  $(t_{1_{0_p}}, t_{2_{0_p}})$ .
2. Check against PEN4 constraint,  $V \leq V_f \left[ t_{1_{0_p}} / D \right] + 4000$  ?
3. If satisfied, the optimal design is  $(t_{1_0}, t_{2_0}) = (t_{1_{0_p}}, t_{2_{0_p}})$ .
4. Else, compute optimal designs for Modified Burch,  $(t_{1_{0_b}}, t_{2_{0_b}})$ , and  
Wilkinson,  $(t_{1_{0_w}}, t_{2_{0_w}})$  Predictors.
5. Compute Wilkinson wall induced by optimal Modified Burch bumper,  $t_{2_w}(t_{1_{0_b}})$ .
6. Compute Burch wall induced by optimal Wilkinson bumper,  $t_{2_b}(t_{1_{0_w}})$ .
7. Find  $(t_{1_0}, t_{2_0}) = \min_{t_1 + t_2} \left[ \left( t_{1_{0_b}}, \max(t_{2_{0_b}}, t_{2_w}(t_{1_{0_b}})) \right), \left( t_{1_{0_w}}, \max(t_{2_{0_w}}, t_{2_b}(t_{1_{0_w}})) \right) \right]$ .

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# B. COMPUTER CODES

BM35-8/21

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## METEOR1

METEOR1 is the meteoroid environment model (see Survivability and Predictor Reference 1) used in the design of protective systems for spacecraft. It is used to define projectile mass/diameter as a preprocessor to IMPACT5 and its derivatives.

METEOR1 takes as inputs the spacecraft exposed surface area, the mission duration, probability of no penetration and altitude, and the particle density. METEOR1 accounts for Earth shielding and gravitational defocussing factors. The output is the critical projectile diameter. A sample input (MET.IN), output (MET.OUT) and program listing (METEOR1.LIS) follow.

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1	!NO. OF CASES
400.	!SURFACE AREA IN SQ. METERS
10.	!DURATION IN YEARS
.97	!PROB. OF NO PENETRATION
500.	!ALT. IN KM
.5	!DENSITY IN GM/CUBIC CM

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INPUT

SURFACE AREA IN SQUARE METERS = 400.0000  
MISSION DURATION IN YEARS = 10.00000  
PROB. OF NO PENETRATION = 0.9700000  
ALTITUDE IN KILOMETERS = 500.0000  
PROJ. DENSITY IN GM/CUBIC CM = 0.5000000

OUTPUT

DIAM= 0.4614225

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12-Aug-1987 13:47:19

VAX FORTRAN

12-Aug-1987 13:47:07

SAI\_USRDISK

```

0001 OPEN(UNIT=9,TYPE='OLD',ACCESS='SEQUENTIAL',NAME='MET.IN')
0002 OPEN(UNIT=10,TYPE='NEW',ACCESS='SEQUENTIAL',NAME='MET.OUT')
0003 READ(9,*)NCASES
0004 DO 10 I=1,NCASES
0005     READ(9,*)SA
0006     READ(9,*)T
0007     READ(9,*)PO
0008     READ(9,*)ALT
0009     READ(9,*)DENS
0010     WRITE (10,*)'          INPUT'
0011     WRITE (10,*)
0012     WRITE(10,*)'          SURFACE AREA IN SQUARE METERS = ',SA
0013     WRITE(10,*)'          MISSION DURATION IN YEARS = ',T
0014     WRITE(10,*)'          PROB. OF NO PENETRATION = ',PO
0015     WRITE(10,*)'          ALTITUDE IN KILOMETERS = ',ALT
0016     WRITE(10,*)'          PROJ. DENSITY IN GM/CUBIC CM = ',DENS
0017     WRITE (10,*)
0018     WRITE (10,*)'          OUTPUT'
0019     WRITE (10,*)
0020     T=31536000.*T
0021     FLUX=-1.*ALOG(PO)/(SA*T)
0022     RA=6371./(6371.+ALT)
0023     GE=.568+.432*RA
0024     THETA=ATAN(6371./SQRT(ALT*(ALT+2.*6371.)))
0025     S=(1.+COS(THETA))/2.
0026     FLUX=FLUX/(GE*S)
0027     F=ALOG10(FLUX)
0028     IF(F.GE.-4.403)THEN
0029         WRITE(10,*)'          MASS IS TOO SMALL'
0030         GO TO 10
0031     ENDIF
0032     IF(F.GT.-7.103.AND.F.LT.-4.403)THEN
0033         RAD=2.509-.25*(14.339+L)
0034         XM=10.**((-1.584+SQRT(RAD))/-.125)
0035     ENDIF
0036     IF(F.LE.-7.103.AND.F.GE.-14.37)THEN
0037         XM=10.**((14.37+F)/-1.213)
0038     ENDIF
0039     IF(F.LT.-14.37)THEN
0040         WRITE(10,*)'          MASS IS TOO LARGE'
0041         GO TO 10
0042     ENDIF
0043     D=(1.91*XM/DENS)**.333
0044     WRITE(10,*)'          DIAM=',D
0045     CONTINUE
0046     END

```

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## DEBRIS1

DEBRIS1 is the space debris environment model (see Survivability and Predictor Reference 2) in the design of protective systems for spacecraft. It is used to define projectile mass/diameter as a preprocessor to IMPACT5 and its derivatives.

DEBRIS1 takes as inputs the spacecraft projected debris area, the mission duration, probability of no penetration, and altitude (currently fixed at 500 Km). The output is the critical projectile diameter. A sample input (DEB.IN), output (DEB.OUT), and program listing (DEBRIS1.LIS) follow.

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1  
574.  
10.  
.97

!NO. OF CASES  
!PROJECTED AREA IN SQ. METERS  
!DURATION IN YEARS  
!PROB. OF NO PENETRATION

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**SAIC**<sup>™</sup>

INPUT

PROJ. AREA IN SQUARE METERS = 574.0000  
MISSION DURATION IN YEARS = 10.00000  
PROB. OF NO PENETRATION = 0.9700000

OUTPUT

DIAM= 0.8446254

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12-Aug-1987 13:52:31

VAX FORTRAN

12-Aug-1987 13:52:24

SAI\_USRDISK

```
0001 OPEN(UNIT=9,TYPE='OLD',ACCESS='SEQUENTIAL',NAME='DEB.IN')
0002 OPEN(UNIT=10,TYPE='NEW',ACCESS='SEQUENTIAL',NAME='DEB.OUT')
0003 READ(9,*)NCASES
0004 DO 10 I=1,NCASES
0005     READ(9,*)AP
0006     READ(9,*)T
0007     READ(9,*)PO
0008     WRITE(10,*)'          INPUT'
0009     WRITE(10,*)
0010     WRITE(10,*)'          PROJ. AREA IN SQUARE METERS = ',AP
0011     WRITE(10,*)'          MISSION DURATION IN YEARS = ',T
0012     WRITE(10,*)'          PROB. OF NO PENETRATION = ',PO
0013     WRITE(10,*)
0014     WRITE(10,*)'          OUTPUT'
0015     WRITE(10,*)
0016     FLUX=-1.*ALOG(PO)/(AP*T)
0017     F=ALOG10(FLUX)
0018     IF(F.GE.-5.46)THEN
0019         D=10.**((F+5.46)/-2.52)
0020     ENDIF
0021     IF(F.LE.-7.0)THEN
0022         D=10.**((F-21.67)/-10.32)
0023     ENDIF
0024     IF(F.LT.-5.46.AND.F.GT.-7.0)THEN
0025         D=10.**((5.46+F)/-.63)
0026     ENDIF
0027     WRITE(10,*)'          DIAM=',D
0028     CONTINUE
0029 END
```

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## IMPACT5

IMPACT5 is a spacecraft protective systems design optimization code. IMPACT5 employs the Geometric Programming optimization technique in evaluating a number of nonlinear piecewise continuous, functional impact predictors. These include the Nysmith, Boeing, Madden, Wilkinson, Burch, and PEN4 predictors. Inputs vary depending on the predictor used, however, typical inputs include projectile characteristics (as determined from METEOR1 or DEBRIS1), design material properties, and general design configuration. In particular, IMPACT5 is an optimization code for a single bumper, single wall configuration. Outputs include the optimal design thicknesses (bumper and wall) and the minimum design weight. Sample input (IMPACT5.IN), output (IMPACT5.OUT) and program listing (IMPACT5.LIS) follow.

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6	!NUMBER OF CASES
1	!NYSMITH PREDICTOR
10.	!PROJ. VELOCITY IN KM/SEC
0.84	!PROJ. DIAMETER IN CM
10.	!BUMPER/WALL SEPARATION IN CM
2	!BOEING PREDICTOR
10.	!PROJ. VELOCITY IN KM/SEC
0.84	!PROJ. DIA. IN CM
2.81	!PROJ. DENSITY IN GM/CUBIC CM
2.81	!BUMPER DENSITY IN GM/CUBIC CM
2.81	!WALL DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
0.401	!WALL MATERIAL CONSTANT
7344000.	!BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000.	!WALL YIELD STRENGTH IN LB/SQUARE FOOT
0.	!IMPACT ANGLE FROM NORMAL
0.85	!NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11	!YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
3	!MADDEN PREDICTOR
10.	!PROJ. VELOCITY IN KM/SEC
0.84	!PROJ. DIA. IN CM
2.81	!PROJ. DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
2.81	!BUMPER/WALL DENSITY IN GM/CUBIC CM
4	!WILKINSON PREDICTOR
10.	!PROJ. VELOCITY IN KM/SEC
0.84	!PROJ. DIA. IN CM
2.81	!PROJ. DENSITY IN GM/CUBIC CM
2.81	!BUMPER DENSITY IN GM/CUBIC CM
2.81	!WALL DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
0.401	!WALL MATERIAL CONSTANT
5	!BURCH PREDICTOR
10.	!PROJ. VELOCITY IN KM/SEC
0.84	!PROJ. DIA. IN CM
2.81	!BUMPER DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
0.	!IMPACT ANGLE FROM NORMAL
0.85	!NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11	!YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
6	!PEN4 PREDICTOR
1.	!PROJ. VELOCITY IN KM/SEC
0.84	!PROJ. DIA. IN CM
2.81	!PROJ. DENSITY IN GM/CUBIC CM
2.81	!BUMPER DENSITY IN GM/CUBIC CM
2.81	!WALL DENSITY IN GM/CUBIC CM
7344000.	!BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000.	!WALL YIELD STRENGTH IN LB/SQUARE FOOT
0.	!IMPACT ANGLE FROM NORMAL

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NYSMITH

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000  
PROJECTILE DIAMETER IN CM = 0.8400000  
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.2575910 CM  
WALL THICKNESS = 0.4791193 CM  
MIN. WEIGHT = 0.7367103 CM  
CMC MIN. WEIGHT = 3799.036 KG

BOEING

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000  
PROJECTILE DIAMETER IN CM = 0.8400000  
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER DENSITY IN GM/CUBIC CM = 2.810000  
WALL DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000  
WALL MATERIAL CONSTANT = 0.4010000  
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.  
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.  
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00  
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000  
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 9.2028841E-02CM  
WALL THICKNESS = 0.4910776 CM  
MIN. WEIGHT = 0.5831065 CM  
CMC MIN. WEIGHT = 2978.630 KG

MADDEN

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000  
PROJECTILE DIAMETER IN CM = 0.8400000  
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.3788331 CM  
WALL THICKNESS = 0.3788331 CM  
MIN. WEIGHT = 0.7576661 CM  
CMC MIN. WEIGHT = 3934.167 KG

WILKINSON

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000  
PROJECTILE DIAMETER IN CM = 0.8400000  
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER DENSITY IN GM/CUBIC CM = 2.810000  
WALL DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000  
WALL MATERIAL CONSTANT = 0.4010000

OUTPUT

BUMPER THICKNESS = 0.2128253 CM  
WALL THICKNESS = 0.2128253 CM  
MIN. WEIGHT = 0.4256506 CM  
CMC MIN. WEIGHT = 2208.558 KG

MODIFIED BURCH

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000  
PROJECTILE DIAMETER IN CM = 0.8400000  
BUMPER DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000  
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00  
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000  
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 9.2028841E-02CM  
WALL THICKNESS = 0.2539445 CM  
MIN. WEIGHT = 0.3459734 CM  
CMC MIN. WEIGHT = 1775.339 KG

PEN4

INPUT

PROJECTILE VELOCITY IN KM/SEC = 1.000000  
PROJECTILE DIAMETER IN CM = 0.8400000  
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER DENSITY IN GM/CUBIC CM = 2.810000  
WALL DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.  
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.  
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00

OUTPUT

BUMPER THICKNESS = 2.1661645E-02CM



WALL THICKNESS = 0.0000000E+00CM  
MIN. WEIGHT = 2.1661645E-02CM  
CMC MIN. WEIGHT = 222.9546 KG

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10-Aug-1987 11:29:15  
10-Aug-1987 11:29:03

VAX FOR  
SAI\_USR

```
0001 OPEN(UNIT=10,TYPE='OLD',NAME='IMPACT5.IN',ACCESS='SEQUENTIAL')
0002 OPEN(UNIT=11,TYPE='NEW',NAME='IMPACT5.OUT',ACCESS='SEQUENTIAL')
0003 READ(10,*)NRUNS
0004 DO 10 I=1,NRUNS
0005     READ(10,*)NCODE
0006     IF(NCODE.EQ.1)GO TO 25
0007     IF(NCODE.EQ.2)GO TO 35
0008     IF(NCODE.EQ.3)GO TO 45
0009     IF(NCODE.EQ.4)GO TO 55
0010     IF(NCODE.EQ.5)GO TO 65
0011     IF(NCODE.EQ.6)GO TO 75
0012 25 READ(10,*)V
0013     READ(10,*)D
0014     READ(10,*)H
0015     WRITE(11,*)'      NYSMITH'
0016     WRITE(11,*)
0017     WRITE(11,*)'      INPUT'
0018     WRITE(11,*)
0019     WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V
0020     WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0021     WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',H
0022     WRITE(11,*)
0023     CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
0024     WRITE(11,*)'      OUTPUT'
0025     WRITE(11,*)
0026     WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0027     WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0028     WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0029     WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0030     WRITE(11,*)
0031     WRITE(11,*)
0032     WRITE(11,*)
0033     GO TO 10
0034 35 READ(10,*)V
0035     READ(10,*)D
0036     READ(10,*)RHOP
0037     READ(10,*)RH01
0038     READ(10,*)RH02
0039     READ(10,*)S
0040     READ(10,*)XL2
0041     READ(10,*)SY1
0042     READ(10,*)SY2
0043     READ(10,*)THETA
0044     READ(10,*)XN
0045     READ(10,*)E1
0046     WRITE(11,*)'      BOEING'
0047     WRITE(11,*)
0048     WRITE(11,*)'      INPUT'
0049     WRITE(11,*)
0050     WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V
0051     WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0052     WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0053     WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0054     WRITE(11,*)'      WALL DENSITY IN GM/CUBIC CM = ',RH02
0055     WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
0056     WRITE(11,*)'      WALL MATERIAL CONSTANT = ',XL2
0057     WRITE(11,*)'      BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
```

```

0058      WRITE(11,*)'      WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
0059      WRITE(11,*)'      IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
0060      WRITE(11,*)'      NUMBER OF PLATES TO PENETRATE AFTER FIRST',
0061      &      '      BUMPER = ',XN
0062      WRITE(11,*)'      BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
0063      &      '      SEC = ',E1
0064      WRITE(11,*)
0065      CALL BOEING(V,D,RHOP,RH01,RH02,S,XL2,SY1,SY2,THETA,
0066      &      XN,E1,T1,T2,WT,WTCMC)
0067      WRITE(11,*)'      OUTPUT'
0068      WRITE(11,*)
0069      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0070      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0071      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0072      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0073      WRITE(11,*)
0074      WRITE(11,*)
0075      WRITE(11,*)
0076      GO TO 10
0077      45      READ(10,*)V
0078      READ(10,*)D
0079      READ(10,*)RHOP
0080      READ(10,*)S
0081      READ(10,*)RHO
0082      WRITE(11,*)'      MADDEN'
0083      WRITE(11,*)
0084      WRITE(11,*)'      INPUT'
0085      WRITE(11,*)
0086      WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V
0087      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0088      WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0089      WRITE(11,*)'      BUMPER/WALL DENSITY IN GM/CUBIC CM = ',RHO
0090      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
0091      WRITE(11,*)
0092      CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
0093      WRITE(11,*)'      OUTPUT'
0094      WRITE(11,*)
0095      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0096      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0097      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0098      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0099      WRITE(11,*)
0100      WRITE(11,*)
0101      WRITE(11,*)
0102      GO TO 10
0103      55      READ(10,*)V
0104      READ(10,*)D
0105      READ(10,*)RHOP
0106      READ(10,*)RH01
0107      READ(10,*)RH02
0108      READ(10,*)S
0109      READ(10,*)XL2
0110      WRITE(11,*)'      WILKINSON'
0111      WRITE(11,*)
0112      WRITE(11,*)'      INPUT'
0113      WRITE(11,*)
0114      WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V

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0115      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0116      WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0117      WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0118      WRITE(11,*)'      WALL DENSITY IN GM/CUBIC CM = ',RH02
0119      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
0120      WRITE(11,*)'      WALL MATERIAL CONSTANT = ',XL2
0121      WRITE(11,*)
0122      CALL WILKINSON(V,D,RHOP,RH01,RH02,S,XL2,
0123      &      T1,T2,WT,WTCMC)
0124      WRITE(11,*)'      OUTPUT'
0125      WRITE(11,*)
0126      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0127      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0128      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0129      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0130      WRITE(11,*)
0131      WRITE(11,*)
0132      WRITE(11,*)
0133      GO TO 10
0134  65      READ(10,*)V
0135      READ(10,*)D
0136      READ(10,*)RH01
0137      READ(10,*)S
0138      READ(10,*)THETA
0139      READ(10,*)XN
0140      READ(10,*)E1
0141  ***** MODIFIED BURCH *****
0142      WRITE(11,*)'      MODIFIED BURCH'
0143      WRITE(11,*)
0144      WRITE(11,*)'      INPUT'
0145      WRITE(11,*)
0146      WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V
0147      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0148      WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0149      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
0150      WRITE(11,*)'      IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
0151      WRITE(11,*)'      NUMBER OF PLATES TO PENETRATE AFTER FIRST',
0152      &      ' BUMPER = ',XN
0153      WRITE(11,*)'      BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
0154      &      ' SEC = ',E1
0155      WRITE(11,*)
0156      WRITE(11,*)'      OUTPUT'
0157      WRITE(11,*)
0158      CALL BURCH(V,D,RH01,S,THETA,
0159      &      XN,E1,T1,T2,WT,WTCMC)
0160      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0161      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0162      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0163      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0164      WRITE(11,*)
0165      WRITE(11,*)
0166      WRITE(11,*)
0167      GO TO 10
0168  75      READ(10,*)V
0169      READ(10,*)D
0170      READ(10,*)RHOP
0171      READ(10,*)RH01

```

```
0172      READ(10,*)RH02
0173      READ(10,*)SY1
0174      READ(10,*)SY2
0175      READ(10,*)THETA
0176      WRITE(11,*)'      PEN4'
0177      WRITE(11,*)
0178      WRITE(11,*)'      INPUT'
0179      WRITE(11,*)
0180      WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V
0181      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0182      WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0183      WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0184      WRITE(11,*)'      WALL DENSITY IN GM/CUBIC CM = ',RH02
0185      WRITE(11,*)'      BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
0186      WRITE(11,*)'      WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
0187      WRITE(11,*)'      IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
0188      WRITE(11,*)
0189      CALL PEN4(V,D,RHOP,RH01,RH02,SY1,SY2,THETA,
0190      &      T1,T2,WT,WTCMC)
0191      WRITE(11,*)'      OUTPUT'
0192      WRITE(11,*)
0193      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0194      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0195      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0196      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0197      WRITE(11,*)
0198      GO TO 10
0199      10  CONTINUE
0200      STOP
0201      END
```

```

0001      SUBROUTINE NYSMITH(V,D,H,T1,T2,WT,WTCMC)
0002      DMAX=0.24*H*V**-0.2
0003      IF(D.GT.DMAX)THEN
0004          WRITE(11,*)'NO SOLUTION--PROJ. DIA. TOO LARGE FOR NYSMITH'
0005          GO TO 16
0006      ENDIF
0007      T1=1.93*V**0.18*D**1.91/H**0.91
0008      T2=1.86*T1
0009      WT=T1+T2
0010      WTCMC=T1**2.+2.*T1*(211.+T2+H)+T2**2.+422.*T2
0011      WTCMC=12.*WTCMC
0012      16      CONTINUE
0013      RETURN
0014      END

```

# PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	214	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	45	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	8	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	267	

# ENTRY POINTS

Address	Type	Name
0-00000000		NYSMITH

# VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	DMAX	AP-0000000C@	R*4	H
AP-00000014@	R*4	T2	AP-00000004@	R*4	V	AP-00000018@	R*4	WT

# LABELS

Address	Label
0-000000D5	16

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```
0001      SUBROUTINE BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
0002      &                XN,E1,T1,T2,WT,WTMC)
0003      ***** PEN4 *****
0004      T1=0.16
0005      V=V*3280.
0006      D=D/30.48
0007      RP=D/2.0
0008      RHOP=RHOP*1.94
0009      RHO1=RHO1*1.94
0010      RHO2=RHO2*1.94
0011      NITSP=0
0012      NITSP=NITSP+1
0013      NP1=0
0014      T1P=T1/30.48
0015      T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
0016      WT=T1P+T2P
0017      IF(NITSP.EQ.1)THEN
0018          T1P1=1.1*T1P
0019          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0020          WT1=T1P1+T2P1
0021      ENDIF
0022      IF(WT1.GT.WT)THEN
0023          T1P1=0.82*T1P1
0024          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0025          WT1=T1P1+T2P1
0026      590      IF(WT1.GT.WT)THEN
0027          GO TO 601
0028      ELSE
0029          T1P=T1P1
0030          T2P=T2P1
0031          WT=WT1
0032          NP1=NP1+1
0033          IF(NP1.EQ.100)THEN
0034              WRITE(11,*)'NO CONVERGENCE IN PEN4'
0035              GO TO 557
0036          ENDIF
0037          T1P1=0.9*T1P1
0038          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0039          WT1=T1P1+T2P1
0040          GO TO 590
0041      ENDIF
0042      ELSE
0043      579      T1P=T1P1
0044          T2P=T2P1
0045          WT=WT1
0046          T1P1=1.1*T1P1
0047          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0048          WT1=T1P1+T2P1
0049          IF(WT1.GT.WT)THEN
0050              GO TO 601
0051          ELSE
0052              NP1=NP1+1
0053              IF(NP1.EQ.100)THEN
0054                  WRITE(11,*)'NO CONVERGENCE IN PEN4'
0055                  GO TO 557
0056              ENDIF
0057              GO TO 579
```



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```
0058         ENDIF
0059         ENDIF
0060 601        CONTINUE
0061         D=30.48*D
0062         RHOP=RHOP/1.94
0063         RH01=RH01/1.94
0064         RH02=RH02/1.94
0065         T1P=30.48*T1P
0066         T2P=30.48*T2P
0067         IF(T1P/D.LE.0.4)VF=4100
0068         IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
0069         VF=VF+4000.
0070         IF(V.LE.VF)THEN
0071             WRITE(11,*)'INSIDE OF PEN4 LIMITS'
0072             T1=T1P
0073             T2=T2P
0074             GO TO 1102
0075         ENDIF
0076 557        CONTINUE
0077 ***** WILKINSON *****
0078         V=V/3280.
0079         T1=0.604*D**2.*RHOP/S
0080         T1=T1*SQRT(V/(XL2*RH01*RH02))
0081         RATIO=D*RHOP/(T1*RH01)
0082         IF(RATIO.GT.1.0)T2=T1
0083         IF(RATIO.LE.1.0)T2=T1/RATIO
0084 ***** MODIFIED BURCH *****
0085         VB=V*3280.
0086         DB=D/2.54
0087         CM=SQRT(E1/RH01)
0088         CM=CM/30.48
0089         SB=S/2.54
0090         IF(THETA.LE.0.001)GO TO 125
0091         CHI=TAN(THETA)-0.5
0092         F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0093         F2=F2+(1.7-12.*T1B/D)*CHI
0094         F3=0.32*(T1B/D)**0.83
0095         F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0096         T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
0097         T2F=T2F*(D/S)**0.71
0098         T2N=F3*(CM/V)**1.33*D/XN
0099         IF(T2N.GE.T2F)T2B=T2N
0100         IF(T2N.LT.T2F)T2B=T2F
0101         T2B=T2B*2.54
0102         IF(T2B.GT.T2)NREGION=3
0103         IF(T2B.GT.T2)T2=T2B
0104         GO TO 155
0105 125        CONTINUE
0106         T1B1=T1/2.54
0107         NITSB=0
0108         XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0109         VDELTA=0.0
0110         DELTA3=0.52
0111 1099       DELTA2=2.33*(1.-1.57*DELTA3)
0112         DELTA1=1.33*(2.*DELTA3-1.)
0113         VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
0114         VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
```

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```
0115      IF(VDELTA1.LT.VDELTA)THEN
0116          DELTA1=1.33*(2.*DELTA3-1.04)
0117          T1B=DELTA1*VDELTA
0118          T2B=VDELTA-T1B
0119          GO TO 499
0120      ENDIF
0121      VDELTA=VDELTA1
0122      DELTA3=DELTA3+0.02
0123      IF(DELTA3.GT.0.63)THEN
0124          T1B=DELTA1*VDELTA
0125          T2B=VDELTA-T1B
0126          GO TO 499
0127      ENDIF
0128      GO TO 1099
0129      499      CONTINUE
0130      ***** COMPARISON OF MODIFIED BURCH AND WILKINSON *****
0131      199      CONTINUE
0132          T10W=T1/2.54
0133          F10W=1.58*(DB/T10W)**0.57+2.80*(T10W/DB)**0.57
0134          T2BT10W=(F10W/XN)**1.71*(CM/VB)**2.29*DB**1.71
0135          T2BT10W=T2BT10W/SB**0.71
0136          T2BT10W=T2BT10W*2.54
0137          RATIOB=(DB*RHOP)/(RH01*T1B)
0138          T2WT10B=0.364*D**3.*RHOP*V/(XL2*RH02*S**2.)
0139          IF(RATIOB.GT.1.0)T2WT10B=T2WT10B*RATIOB
0140          IF(T2BT10W.GT.T2)T2=T2BT10W
0141          T2B=T2B*2.54
0142          IF(T2WT10B.GT.T2B)T2B=T2WT10B
0143          T1B=T1B*2.54
0144          IF(T1B+T2B.LT.T1+T2)THEN
0145              T1=T1B
0146              T2=T2B
0147          ENDIF
0148          155      CONTINUE
0149          1102      IF(T2.LE.0.01)THEN
0150              WRITE(11,*)'PRESSURE CONSTRAINT ON WALL IN EFFECT'
0151              SIGMA=SY2/144.
0152              T2=3099.1/SIGMA
0153          ENDIF
0154          WT=T1+T2
0155          R12=211.
0156          R22=211.+T2
0157          R11=211.+T2+S
0158          R21=211.+T1+T2+S
0159          VB=4.27*(R21**2.-R11**2.)
0160          VW=4.27*(R22**2.-R12**2.)
0161          WTCMC=RH01*VB+RH02*VW
0162          156      RETURN
0163      END
```

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```
0001      FUNCTION FT2B(DB,T1B,XN,CM,VB,SB)
0002      F1=2.42*(DB/T1B)**0.33+4.26*(T1B/DB)**0.33
0003      F1=F1-4.18
0004      FT2B=(F1/XN)**1.71*(CM/VB)**2.29*DB**1.71/SB**0.71
0005      RETURN
0006      END
```

#### PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	163	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	167	

#### ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2B

#### VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000010@	R*4	CM	AP-00000004@	R*4	DB	**	R*4	F1
AP-00000008@	R*4	T1B	AP-00000014@	R*4	VB	AP-0000000C@	R*4	XN

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0001      FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P)
0002      A=1.33*RHOP*(V*RP)**2.
0003      B=8.0*SY1*EXP(-3.125E-04*V)/COS(THETA)
0004      C=1.33*RHOP*RP**2.0
0005      D1=RP*RH01/COS(THETA)
0006      XK1=1.67*(RHOP/(2.*SY2))**0.31
0007      XK1=XK1*(0.281*D*RHOP/RH02)**0.33
0008      XK1=XK1*COS(THETA)
0009      C1P1=(A-B*T1P)/(C+D1*T1P)
0010      IF(C1P1.LE.0.001)THEN
0011          FT2P=0.0
0012          GO TO 999
0013      ENDIF
0014      FT2P=XK1*C1P1**0.31
0015      999      RETURN
0016      END

```

## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	222	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	226	

## ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2P

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
**	R*4	A	**	R*4	B	**	R*4	C
AP-00000020@	R*4	D	**	R*4	D1	AP-00000018@	R*4	RH01
AP-00000004@	R*4	RHOP	AP-0000000C@	R*4	RP	AP-00000010@	R*4	SY1
AP-00000028@	R*4	T1P	AP-00000014@	R*4	THETA	AP-00000008@	R*4	V

## LABELS

Address	Label
0-000000D9	999

```

0001      SUBROUTINE MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
0002      V=V*1.E05
0003      T1=0.009*SQRT(V)*RHOP*D**2.0
0004      T1=T1/(S*RHO**1.5)
0005      T2=T1
0006      WT=T1+T2
0007      R12=211.
0008      R22=211.+T2
0009      R11=211.+T2+S
0010      R21=211.+T1+T2+S
0011      VB=4.27*(R21**2.-R11**2.)
0012      VW=4.27*(R22**2.-R12**2.)
0013      WTCMC=RHO*(VB+VW)
0014      RETURN
0015      END

```

#### PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	159	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	159	

#### ENTRY POINTS

Address	Type	Name
0-00000000		MADDEN

#### VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	R11	**	R*4	R12
**	R*4	R22	AP-00000014@	R*4	RHO	AP-0000000C@	R*4	RHOP
AP-00000018@	R*4	T1	AP-0000001C@	R*4	T2	AP-00000004@	R*4	V
**	R*4	VW	AP-00000020@	R*4	WT	AP-00000024@	R*4	WTCMC

#### FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

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```

0001      SUBROUTINE WILKINSON(V,D,RHOP,RH01,RH02,S,XL2,
0002      &      T1,T2,WT,WTCMC)
0003      T1=0.604*D**2.*RHOP/S
0004      T1=T1*SQRT(V/(XL2*RH01*RH02))
0005      RATIO=D*RHOP/(T1*RH01)
0006      IF(RATIO.GT.1.0)T2=T1
0007      IF(RATIO.LE.1.0)T2=T1/RATIO
0008      WT=T1+T2
0009      R12=211.
0010      R22=211.+T2
0011      R11=211.+T2+S
0012      R21=211.+T1+T2+S
0013      VB=4.27*(R21**2.-R11**2.)
0014      VW=4.27*(R22**2.-R12**2.)
0015      WTCMC=RH01*VB+RH02*VW
0016      RETURN
0017      END

```

## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	181	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	181	

## ENTRY POINTS

Address	Type	Name
0-00000000		WILKINSON

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	R11	**	R*4	R12
**	R*4	R22	**	R*4	RATIO	AP-00000010@	R*4	RH01
AP-0000000C@	R*4	RHOP	AP-00000018@	R*4	S	AP-00000020@	R*4	T1
AP-00000004@	R*4	V	**	R*4	VB	**	R*4	VW
AP-0000002C@	R*4	WTCMC	AP-0000001C@	R*4	XL2			

## FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

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```
0001 ***** MODIFIED BURCH *****
0002 SUBROUTINE BURCH(V,D,RH01,S,THETA,
0003 & XN,E1,T1,T2,WT,WTCMC)
0004 VB=V*3280.
0005 DB=D/2.54
0006 CM=SQRT(E1/RH01)
0007 CM=CM/30.48
0008 SB=S/2.54
0009 IF(THETA.LE.0.001)GO TO 425
0010 CHI=TAN(THETA)-0.5
0011 F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0012 F2=F2+(1.7-12.*T1B/D)*CHI
0013 F3=0.32*(T1B/D)**0.83
0014 F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0015 T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
0016 T2F=T2F*(D/S)**0.71
0017 T2N=F3*(CM/V)**1.33*D/XN
0018 IF(T2N.GE.T2F)T2B=T2N
0019 IF(T2N.LT.T2F)T2B=T2F
0020 T2B=T2B*2.54
0021 IF(T2B.GT.T2)NREGION=3
0022 IF(T2B.GT.T2)T2=T2B
0023 GO TO 499
0024 425 CONTINUE
0025 NITSB=0
0026 XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0027 VDELTA=0.0
0028 DELTA3=0.52
0029 1099 DELTA2=2.33*(1.-1.57*DELTA3)
0030 DELTA1=1.33*(2.*DELTA3-1.)
0031 VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
0032 VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
0033 IF(VDELTA1.LT.VDELTA)THEN
0034 DELTA1=1.33*(2.*DELTA3-1.04)
0035 T1=DELTA1*VDELTA
0036 T2=VDELTA-T1
0037 GO TO 499
0038 ENDIF
0039 VDELTA=VDELTA1
0040 DELTA3=DELTA3+0.02
0041 IF(DELTA3.GT.0.63)THEN
0042 T1=DELTA1*VDELTA
0043 T2=VDELTA-T1
0044 GO TO 499
0045 ENDIF
0046 GO TO 1099
0047 499 CONTINUE
0048 T1=T1*2.54
0049 T2=T2*2.54
0050 WT=T1+T2
0051 R12=211.
0052 R22=211.+T2
0053 R11=211.+T2+S
0054 R21=211.+T1+T2+S
0055 VB=4.27*(R21**2.-R11**2.)
0056 VW=4.27*(R22**2.-R12**2.)
0057 WTCMC=RH01*VB+2.81*VW
```

VAX FC

SAI [REDACTED]

```

0001 SUBROUTINE PEN4(V,D,RHOP,RH01,RH02,SY1,SY2,THETA,
0002 & T1,T2,WT,WTCMC)
0003 T1=0.16
0004 V=V*3280.
0005 D=D/30.48
0006 RP=D/2.0
0007 RHOP=RHOP*1.94
0008 RH01=RH01*1.94
0009 RH02=RH02*1.94
0010 NITSP=0
0011 NITSP=NITSP+1
0012 NP1=0
0013 T1P=T1/30.48
0014 T2P=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P)
0015 WT=T1P+T2P
0016 IF(NITSP.EQ.1)THEN
0017     T1P1=1.1*T1P
0018     T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0019     WT1=T1P1+T2P1
0020 ENDIF
0021 IF(WT1.GT.WT)THEN
0022     T1P1=0.82*T1P1
0023     T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0024     WT1=T1P1+T2P1
0025 588 IF(WT1.GT.WT)THEN
0026     GO TO 599
0027 ELSE
0028     T1P=T1P1
0029     T2P=T2P1
0030     WT=WT1
0031     NP1=NP1+1
0032     IF(NP1.EQ.100)THEN
0033         WRITE(11,*)'NO CONVERGENCE IN PEN4'
0034         GO TO 555
0035     ENDIF
0036     T1P1=0.9*T1P1
0037     T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0038     WT1=T1P1+T2P1
0039     GO TO 588
0040 ENDIF
0041 ELSE
0042 577 T1P=T1P1
0043     T2P=T2P1
0044     WT=WT1
0045     T1P1=1.1*T1P1
0046     T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0047     WT1=T1P1+T2P1
0048     IF(WT1.GT.WT)THEN
0049         GO TO 599
0050     ELSE
0051         NP1=NP1+1
0052         IF(NP1.EQ.100)THEN
0053             WRITE(11,*)'NO CONVERGENCE IN PEN4'
0054             GO TO 555
0055         ENDIF
0056         GO TO 577
0057     ENDIF

```



PEN4

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```

0058      ENDIF
0059      599      CONTINUE
0060      D=30.48*D
0061      T1P=30.48*T1P
0062      T2P=30.48*T2P
0063      IF(T1P/D.LE.0.4)VF=4100
0064      IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
0065      VF=VF+4000.
0066      IF(V.GT.VF)THEN
0067          WRITE(11,*)'OUTSIDE OF PEN4 LIMITS'
0068          GO TO 1100
0069      ENDIF
0070      T1=T1P
0071      T2=T2P
0072      555      CONTINUE
0073      WT=T1+T2
0074      R12=211.
0075      R22=211.+T2
0076      R11=211.+T2+10.
0077      R21=211.+T1+T2+10.
0078      VB=4.27*(R21**2.-R11**2.)
0079      VW=4.27*(R22**2.-R12**2.)
0080      WTCMC=RH01*VB+RH02*VW
0081      1100     RETURN
0082      END

```

## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	775	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	44	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	120	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	939	

## ENTRY POINTS

Address	Type	Name
0-00000000		PEN4

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	I*4	NITSP	**	I*4	NP1
**	R*4	R12	**	R*4	R21	**	R*4	R22
AP-00000014@	R*4	RH02	AP-0000000C@	R*4	RH0P	2-00000000	R*4	RP
AP-0000001C@	R*4	SY2	AP-00000024@	R*4	T1	2-00000004	R*4	T1P
AP-00000028@	R*4	T2	**	R*4	T2P	**	R*4	T2P1
AP-00000004@	R*4	V	**	R*4	VB	2-0000000C	R*4	VF

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## IMPACT5V

IMPACT5V is a spacecraft protective systems design optimization code similar to IMPACT5. IMPACT5V differs from IMPACT5 in that the optimal design is weighted according to the chosen space debris velocity probability distribution. IMPACT5V employs the Geometric Programming optimization technique in evaluating a number of nonlinear piecewise continuous, functional impact predictors. These include the Nysmith, Boeing, Madden, Wilkinson, and Burch predictors. Inputs vary depending on the predictor used, however, typical inputs include the space debris velocity distribution file, projectile characteristics (as determined from METEOR1 or DEBRIS1), design material properties, and general design configuration. In particular, IMPACT5V is an optimization code for a single bumper, single wall configuration. Outputs include the optimal design thicknesses (bumper and wall) and the minimum design weight. The velocity distribution files for 500 Km altitude and 30 degree inclination (500KM30DEG.DAT) and 60 degree inclination (500KM60 DEG.DAT) follow. The file being used must be assigned to FOR012 before running IMPACT5V. Sample input (IMPACT5V.IN), output (IMPACT5V.OUT), and program listing (IMPACT5V.LIS) follow the velocity distribution files.

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1	0.005
2	0.005
3	0.02
4	0.05
5	0.10
6	0.05
7	0.075
8	0.08
9	0.07
10	0.23
11	0.155
12	0.08
13	0.05
14	0.02
15	0.005
16	0.005

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1	0.01
2	0.01
3	0.01
4	0.01
5	0.03
6	0.03
7	0.01
8	0.01
9	0.005
10	0.09
11	0.09
12	0.07
13	0.28
14	0.28
15	0.065
16	0.005

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5	!NUMBER OF CASES
1	!NYSMITH PREDICTOR
0.84	!PROJ. DIAMETER IN CM
10.	!BUMPER/WALL SEPARATION IN CM
2	!BOEING PREDICTOR
0.84	!PROJ. DIA. IN CM
2.81	!PROJ. DENSITY IN GM/CUBIC CM
2.81	!BUMPER DENSITY IN GM/CUBIC CM
2.81	!WALL DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
0.401	!WALL MATERIAL CONSTANT
7344000.	!BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000.	!WALL YIELD STRENGTH IN LB/SQUARE FOOT
0.	!IMPACT ANGLE FROM NORMAL
0.85	!NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11	!YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
3	!MADDEN PREDICTOR
0.84	!PROJ. DIA. IN CM
2.81	!PROJ. DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
2.81	!BUMPER/WALL DENSITY IN GM/CUBIC CM
4	!WILKINSON PREDICTOR
0.84	!PROJ. DIA. IN CM
2.81	!PROJ. DENSITY IN GM/CUBIC CM
2.81	!BUMPER DENSITY IN GM/CUBIC CM
2.81	!WALL DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
0.401	!WALL MATERIAL CONSTANT
5	!BURCH PREDICTOR
0.84	!PROJ. DIA. IN CM
2.81	!BUMPER DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
0.	!IMPACT ANGLE FROM NORMAL
0.85	!NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11	!YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC

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NYSMITH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000  
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.2498978 CM  
WALL THICKNESS = 0.4648098 CM  
MIN. WEIGHT = 0.7147076 CM  
CMC MIN. WEIGHT = 3685.385 KG

BOEING

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000  
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER DENSITY IN GM/CUBIC CM = 2.810000  
WALL DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000  
WALL MATERIAL CONSTANT = 0.4010000  
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.  
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.  
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00  
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000  
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

INSIDE OF PEN4 LIMITS

INSIDE OF PEN4 LIMITS

OUTPUT

BUMPER THICKNESS = 0.1605087 CM  
WALL THICKNESS = 0.5884032 CM  
MIN. WEIGHT = 0.7489119 CM  
CMC MIN. WEIGHT = 3837.381 KG

MADDEN

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000  
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.3522651 CM  
WALL THICKNESS = 0.3522651 CM  
MIN. WEIGHT = 0.7045302 CM  
CMC MIN. WEIGHT = 3657.869 KG

WILKINSON

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000  
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER DENSITY IN GM/CUBIC CM = 2.810000  
WALL DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000  
WALL MATERIAL CONSTANT = 0.4010000

OUTPUT

BUMPER THICKNESS = 0.1978996 CM  
WALL THICKNESS = 0.1978996 CM  
MIN. WEIGHT = 0.3957993 CM  
CMC MIN. WEIGHT = 2053.512 KG

MODIFIED BURCH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000  
BUMPER DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000  
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00  
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000  
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 0.1434212 CM  
WALL THICKNESS = 0.6418241 CM  
MIN. WEIGHT = 0.7852453 CM  
CMC MIN. WEIGHT = 4017.877 KG

10-Aug-1987 11:43:04  
10-Aug-1987 11:42:56

VAX FORTRAN  
SAI\_USRDISK

```
0001      DIMENSION XPV(16)
0002      OPEN(UNIT=12,TYPE='OLD',ACCESS='SEQUENTIAL')
0003      OPEN(UNIT=10,TYPE='OLD',NAME='IMPACT5V.IN',ACCESS='SEQUENTIAL')
0004      OPEN(UNIT=11,TYPE='NEW',NAME='IMPACT5V.OUT',ACCESS='SEQUENTIAL')
0005      DO 24 I=1,16
0006          READ(12,*)IV,XPV(IV)
0007 24      CONTINUE
0008          READ(10,*)NRUNS
0009          DO 10 I=1,NRUNS
0010              READ(10,*)NCODE
0011              IF(NCODE.EQ.1)GO TO 25
0012              IF(NCODE.EQ.2)GO TO 35
0013              IF(NCODE.EQ.3)GO TO 45
0014              IF(NCODE.EQ.4)GO TO 55
0015              IF(NCODE.EQ.5)GO TO 65
0016 25      READ(10,*)D
0017          READ(10,*)H
0018          WRITE(11,*)'      NYSMITH'
0019          WRITE(11,*)
0020          WRITE(11,*)'      INPUT'
0021          WRITE(11,*)
0022          WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0023          WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',H
0024          WRITE(11,*)
0025          T1T=0.0
0026          T2T=0.0
0027          DO 26 J=1,16
0028              V=FLOAT(J)
0029              CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
0030              T1T=T1T+T1*XPV(J)
0031              T2T=T2T+T2*XPV(J)
0032 26      CONTINUE
0033          T1=T1T
0034          T2=T2T
0035          WT=T1+T2
0036          WTCMC=T1**2.+2.*T1*(211.+T2+H)+T2**2.+422.*T2
0037          WTCMC=12.*WTCMC
0038          WRITE(11,*)'      OUTPUT'
0039          WRITE(11,*)
0040          WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0041          WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0042          WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0043          WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0044          WRITE(11,*)
0045          WRITE(11,*)
0046          WRITE(11,*)
0047          GO TO 10
0048 35      READ(10,*)D
0049          READ(10,*)RHOP
0050          READ(10,*)RH01
0051          READ(10,*)RH02
0052          READ(10,*)S
0053          READ(10,*)XL2
0054          READ(10,*)SY1
0055          READ(10,*)SY2
0056          READ(10,*)THETA
0057          READ(10,*)XN
```

```

58      READ(10,*)E1
59      WRITE(11,*)'      BOEING'
60      WRITE(11,*)
61      WRITE(11,*)'      INPUT'
62      WRITE(11,*)
63      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
64      WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
65      WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RH01
66      WRITE(11,*)'      WALL DENSITY IN GM/CUBIC CM = ',RH02
67      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
68      WRITE(11,*)'      WALL MATERIAL CONSTANT = ',XL2
69      WRITE(11,*)'      BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
70      WRITE(11,*)'      WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
71      WRITE(11,*)'      IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
72      WRITE(11,*)'      NUMBER OF PLATES TO PENETRATE AFTER FIRST',
73      &          '      BUMPER = ',XN
74      &      WRITE(11,*)'      BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
75      &          '      SEC = ',E1
76      WRITE(11,*)
77      T1T=0.0
78      T2T=0.0
79      DO 36 J=1,16
80      V=FLOAT(J)
81      CALL BOEING(V,D,RHOP,RH01,RH02,S,XL2,SY1,SY2,THETA,
82      &          XN,E1,T1,T2,WT,WTCMC)
83      T1T=T1T+XPV(J)*T1
84      T2T=T2T+XPV(J)*T2
85      36  CONTINUE
86      T1=T1T
87      T2=T2T
88      WT=T1+T2
89      R12=211.
90      R22=211.+T2
91      R11=211.+T2+S
92      R21=211.+T1+T2+S
93      VB=4.27*(R21**2.-R11**2.)
94      VW=4.27*(R22**2.-R12**2.)
95      WTCMC=RH01*VB+RH02*VW
96      WRITE(11,*)'      OUTPUT'
97      WRITE(11,*)
98      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
99      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
100     WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
101     WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
102     WRITE(11,*)
103     WRITE(11,*)
104     WRITE(11,*)
105     GO TO 10
106     45  READ(10,*)D
107     READ(10,*)RHOP
108     READ(10,*)S
109     READ(10,*)RHO
110     WRITE(11,*)'      MADDEN'
111     WRITE(11,*)
112     WRITE(11,*)'      INPUT'
113     WRITE(11,*)
114     WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D

```

```

0115      WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0116      WRITE(11,*)'      BUMPER/WALL DENSITY IN GM/CUBIC CM = ',RHO
0117      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
0118      WRITE(11,*)
0119      T1T=0.0
0120      T2T=0.0
0121      DO 46 J=1,16
0122      V=FLOAT(J)
0123      CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
0124      T1T=T1T+T1*XPV(J)
0125      T2T=T2T+T2*XPV(J)
0126      46      CONTINUE
0127      T1=T1T
0128      T2=T2T
0129      WT=T1+T2
0130      R12=211.
0131      R22=211.+T2
0132      R11=211.+T2+S
0133      R21=211.+T1+T2+S
0134      VB=4.27*(R21**2.-R11**2.)
0135      VW=4.27*(R22**2.-R12**2.)
0136      WTCMC=RHO*(VB+VW)
0137      WRITE(11,*)'      OUTPUT'
0138      WRITE(11,*)
0139      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0140      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0141      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0142      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0143      WRITE(11,*)
0144      WRITE(11,*)
0145      WRITE(11,*)
0146      GO TO 10
0147      55      READ(10,*)D
0148      READ(10,*)RHOP
0149      READ(10,*)RH01
0150      READ(10,*)RH02
0151      READ(10,*)S
0152      READ(10,*)XL2
0153      WRITE(11,*)'      WILKINSON'
0154      WRITE(11,*)
0155      WRITE(11,*)'      INPUT'
0156      WRITE(11,*)
0157      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0158      WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0159      WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0160      WRITE(11,*)'      WALL DENSITY IN GM/CUBIC CM = ',RH02
0161      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
0162      WRITE(11,*)'      WALL MATERIAL CONSTANT = ',XL2
0163      WRITE(11,*)
0164      T1T=0.0
0165      T2T=0.0
0166      DO 56 J=1,16
0167      V=FLOAT(J)
0168      CALL WILKINSON(V,D,RHOP,RH01,RH02,S,XL2,
0169      &      T1,T2,WT,WTCMC)
0170      T1T=T1T+T1*XPV(J)
0171      T2T=T2T+T2*XPV(J)

```

```

0172      56      CONTINUE
0173          T1=T1T
0174          T2=T2T
0175          WT=T1+T2
0176          R12=211.
0177          R22=211.+T2
0178          R11=211.+T2+S
0179          R21=211.+T1+T2+S
0180          VB=4.27*(R21**2.-R11**2.)
0181          VW=4.27*(R22**2.-R12**2.)
0182          WTCMC=RH01*VB+RH02*VW
0183          WRITE(11,*)'          OUTPUT'
0184          WRITE(11,*)
0185          WRITE(11,*)'          BUMPER THICKNESS = ',T1,'CM'
0186          WRITE(11,*)'          WALL THICKNESS = ',T2,'CM'
0187          WRITE(11,*)'          MIN. WEIGHT = ',WT,'CM'
0188          WRITE(11,*)'          CMC MIN. WEIGHT = ',WTCMC,'KG'
0189          WRITE(11,*)
0190          WRITE(11,*)
0191          WRITE(11,*)
0192          GO TO 10
0193      65      READ(10,*)D
0194          READ(10,*)RH01
0195          READ(10,*)S
0196          READ(10,*)THETA
0197          READ(10,*)XN
0198          READ(10,*)E1
0199      ***** MODIFIED BURCH *****
0200          WRITE(11,*)'          MODIFIED BURCH'
0201          WRITE(11,*)
0202          WRITE(11,*)'          INPUT'
0203          WRITE(11,*)
0204          WRITE(11,*)'          PROJECTILE DIAMETER IN CM = ',D
0205          WRITE(11,*)'          BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0206          WRITE(11,*)'          BUMPER/WALL SEPARATION IN CM = ',S
0207          WRITE(11,*)'          IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
0208          WRITE(11,*)'          NUMBER OF PLATES TO PENETRATE AFTER FIRST',
0209          &          ' BUMPER = ',XN
0210          WRITE(11,*)'          BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
0211          &          ' SEC = ',E1
0212          WRITE(11,*)
0213          T1T=0.0
0214          T2T=0.0
0215          DO 66 J=1,16
0216              V=FLOAT(J)
0217              CALL BURCH(V,D,RH01,S,THETA,
0218              &          XN,E1,T1,T2,WT,WTCMC)
0219              T1T=T1T+T1*XPV(J)
0220              T2T=T2T+T2*XPV(J)
0221      66      CONTINUE
0222          T1=T1T
0223          T2=T2T
0224          WT=T1+T2
0225          R12=211.
0226          R22=211.+T2
0227          R11=211.+T2+S
0228          R21=211.+T1+T2+S

```



```

0229      VB=4.27*(R21**2.-R11**2.)
0230      VW=4.27*(R22**2.-R12**2.)
0231      WTCMC=RH01*VB+2.81*VW
0232      WRITE(11,*)'          OUTPUT'
0233      WRITE(11,*)
0234      WRITE(11,*)'          BUMPER THICKNESS = ',T1,'CM'
0235      WRITE(11,*)'          WALL THICKNESS = ',T2,'CM'
0236      WRITE(11,*)'          MIN. WEIGHT = ',WT,'CM'
0237      WRITE(11,*)'          CMC MIN. WEIGHT = ',WTCMC,'KG'
0238      WRITE(11,*)
0239      WRITE(11,*)
0240      WRITE(11,*)
0241      GO TO 10
0242  10    CONTINUE
0243      STOP
0244      END

```

## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	4728	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	741	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	692	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	6161	

## ENTRY POINTS

Address	Type	Name
0-00000000		IMPACT5V\$MAIN

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
2-0000004C	R*4	D	2-0000008C	R*4	E1	2-00000050	R*4	H
2-00000040	I*4	IV	**	I*4	J	2-00000048	I*4	NCODE
**	R*4	R11	**	R*4	R12	**	R*4	R21
2-00000090	R*4	RH0	2-0000006C	R*4	RH01	2-00000070	R*4	RH02
2-00000074	R*4	S	2-0000007C	R*4	SY1	2-00000080	R*4	SY2
**	R*4	T1T	2-0000005C	R*4	T2	**	R*4	T2T
2-00000054	R*4	V	**	R*4	VB	**	R*4	VW
2-00000064	R*4	WTCMC	2-00000078	R*4	XL2	2-00000088	R*4	XN

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VAX FORTRAN  
SAI\_USRDIS

```
0001      SUBROUTINE NYSMITH(V,D,H,T1,T2,WT,WTCMC)
0002      DMAX=0.24*H*V**-0.2
0003      IF(D.GT.DMAX)THEN
0004          WRITE(11,*)'      NO SOLUTION--PROJ. DIA. TOO LARGE FOR NYSMITH'
0005          GO TO 16
0006      ENDIF
0007      T1=1.93*V**0.18*D**1.91/H**0.91
0008      T2=1.86*T1
0009      16      CONTINUE
0010      RETURN
0011      END
```

#### PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	150	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	49	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	8	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	207	

#### ENTRY POINTS

Address	Type	Name
0-00000000		NYSMITH

#### VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	DMAX	AP-0000000C@	R*4	H
AP-00000014@	R*4	T2	AP-00000004@	R*4	V	AP-00000018@	R*4	WT

#### LABELS

Address	Label
0-00000095	16

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VAX FORTRAN  
CAT USRDIS

```

0001      SUBROUTINE BOEING(V,D,RHOP,RH01,RH02,S,XL2,SY1,SY2,THETA,
0002      &                XN,E1,T1,T2,WT,WTCMC)
0003      ***** PEN4 *****
0004      T1=0.16
0005      V=V*3280.
0006      D=D/30.48
0007      RP=D/2.0
0008      RHOP=RHOP*1.94
0009      RH01=RH01*1.94
0010      RH02=RH02*1.94
0011      NITSP=0
0012      NITSP=NITSP+1
0013      NP1=0
0014      T1P=T1/30.48
0015      T2P=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P)
0016      WT=T1P+T2P
0017      IF(NITSP.EQ.1)THEN
0018          T1P1=1.1*T1P
0019          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0020          WT1=T1P1+T2P1
0021      ENDIF
0022      IF(WT1.GT.WT)THEN
0023          T1P1=0.82*T1P1
0024          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0025          WT1=T1P1+T2P1
0026      590      IF(WT1.GT.WT)THEN
0027          GO TO 601
0028      ELSE
0029          T1P=T1P1
0030          T2P=T2P1
0031          WT=WT1
0032          NP1=NP1+1
0033          IF(NP1.EQ.100)THEN
0034              WRITE(11,*)'      NO CONVERGENCE IN PEN4'
0035              GO TO 557
0036          ENDIF
0037          T1P1=0.9*T1P1
0038          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0039          WT1=T1P1+T2P1
0040          GO TO 590
0041      ENDIF
0042      579      ELSE
0043          T1P=T1P1
0044          T2P=T2P1
0045          WT=WT1
0046          T1P1=1.1*T1P1
0047          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0048          WT1=T1P1+T2P1
0049          IF(WT1.GT.WT)THEN
0050              GO TO 601
0051          ELSE
0052              NP1=NP1+1
0053              IF(NP1.EQ.100)THEN
0054                  WRITE(11,*)'      NO CONVERGENCE IN PEN4'
0055                  GO TO 557
0056              ENDIF
0057              GO TO 579

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0058         ENDIF
0059         ENDIF
0060 601        CONTINUE
0061           D=30.48*D
0062           RHOP=RHOP/1.94
0063           RH01=RH01/1.94
0064           RH02=RH02/1.94
0065           T1P=30.48*T1P
0066           T2P=30.48*T2P
0067           IF(T1P/D.LE.0.4)VF=4100
0068           IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
0069           VF=VF+4000.
0070           IF(V.LE.VF)THEN
0071             WRITE(11,*)'    INSIDE OF PEN4 LIMITS'
0072             T1=T1P
0073             T2=T2P
0074             GO TO 1102
0075           ENDIF
0076 557        CONTINUE
0077 ***** WILKINSON *****
0078           V=V/3280.
0079           T1=0.604*D**2.*RHOP/S
0080           T1=T1*SQRT(V/(XL2*RH01*RH02))
0081           RATIO=D*RHOP/(T1*RH01)
0082           IF(RATIO.GT.1.0)T2=T1
0083           IF(RATIO.LE.1.0)T2=T1/RATIO
0084 ***** MODIFIED BURCH *****
0085           VB=V*3280.
0086           DB=D/2.54
0087           CM=SQRT(E1/RH01)
0088           CM=CM/30.48
0089           SB=S/2.54
0090           IF(THETA.LE.0.001)GO TO 125
0091           CHI=TAN(THETA)-0.5
0092           F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0093           F2=F2+(1.7-12.*T1B/D)*CHI
0094           F3=0.32*(T1B/D)**0.83
0095           F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0096           T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
0097           T2F=T2F*(D/S)**0.71
0098           T2N=F3*(CM/V)**1.33*D/XN
0099           IF(T2N.GE.T2F)T2B=T2N
0100           IF(T2N.LT.T2F)T2B=T2F
0101           T2B=T2B*2.54
0102           IF(T2B.GT.T2)NREGION=3
0103           IF(T2B.GT.T2)T2=T2B
0104           GO TO 155
0105 125        CONTINUE
0106           T1B1=T1/2.54
0107           NITSB=0
0108           XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0109           VDELTA=0.0
0110           DELTA3=0.52
0111 1099       DELTA2=2.33*(1.-1.57*DELTA3)
0112           DELTA1=1.33*(2.*DELTA3-1.)
0113           VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
0114           VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3

```

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```

0115      IF(VDELTA1.LT.VDELTA)THEN
0116          DELTA1=1.33*(2.*DELTA3-1.04)
0117          T1B=DELTA1*VDELTA
0118          T2B=VDELTA-T1B
0119          GO TO 499
0120      ENDIF
0121      VDELTA=VDELTA1
0122      DELTA3=DELTA3+0.02
0123      IF(DELTA3.GT.0.63)THEN
0124          T1B=DELTA1*VDELTA
0125          T2B=VDELTA-T1B
0126          GO TO 499
0127      ENDIF
0128      GO TO 1099
0129  499      CONTINUE
0130  ***** COMPARISON OF MODIFIED BURCH AND WILKINSON *****
0131  199      CONTINUE
0132          T10W=T1/2.54
0133          F10W=1.58*(DB/T10W)**0.57+2.80*(T10W/DB)**0.57
0134          T2BT10W=(F10W/XN)**1.71*(CM/VB)**2.29*DB**1.71
0135          T2BT10W=T2BT10W/SB**0.71
0136          T2BT10W=T2BT10W*2.54
0137          RATIOB=(DB*RHOP)/(RH01*T1B)
0138          T2WT10B=0.364*D**3.*RHOP*V/(XL2*RH02*S**2.)
0139          IF(RATIOB.GT.1.0)T2WT10B=T2WT10B*RATIOB
0140          IF(T2BT10W.GT.T2)T2=T2BT10W
0141          T2B=T2B*2.54
0142          IF(T2WT10B.GT.T2B)T2B=T2WT10B
0143          T1B=T1B*2.54
0144          IF(T1B+T2B.LT.T1+T2)THEN
0145              T1=T1B
0146              T2=T2B
0147          ENDIF
0148  155      CONTINUE
0149  1102      IF(T2.LE.0.01)THEN
0150              SIGMA=SY2/144.
0151              T2=3099.1/SIGMA
0152          ENDIF
0153  156      RETURN
0154      END

```

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```

0001      FUNCTION FT2B(DB,T1B,XN,CM,VB,SB)
0002      F1=2.42*(DB/T1B)**0.33+4.26*(T1B/DB)**0.33
0003      F1=F1-4.18
0004      FT2B=(F1/XN)**1.71*(CM/VB)**2.29*DB**1.71/SB**0.71
0005      RETURN
0006      END

```

## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	163	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	167	

## ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2B

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000010@	R*4	CM	AP-00000004@	R*4	DB	**	R*4	F1
AP-00000008@	R*4	T1B	AP-00000014@	R*4	VB	AP-0000000C@	R*4	XN

```

0001      FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P)
0002      A=1.33*RHOP*(V*RP)**2.
0003      B=8.0*SY1*EXP(-3.125E-04*V)/COS(THETA)
0004      C=1.33*RHOP*RP**2.0
0005      D1=RP*RH01/COS(THETA)
0006      XK1=1.67*(RHOP/(2.*SY2))**0.31
0007      XK1=XK1*(0.281*D*RHOP/RH02)**0.33
0008      XK1=XK1*COS(THETA)
0009      C1P1=(A-B*T1P)/(C+D1*T1P)
0010      IF(C1P1.LE.0.001)THEN
0011          FT2P=0.0
0012          GO TO 999
0013      ENDIF
0014      FT2P=XK1*C1P1**0.31
0015      RETURN
0016      END

```

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## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	222	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	226	

## ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2P

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
**	R*4	A	**	R*4	B	**	R*4	C
AP-00000020@	R*4	D	**	R*4	D1	AP-00000018@	R*4	RH01
AP-00000004@	R*4	RHOP	AP-0000000C@	R*4	RP	AP-00000010@	R*4	SY1
AP-00000028@	R*4	T1P	AP-00000014@	R*4	THETA	AP-00000008@	R*4	V

## LABELS

Address	Label
0-000000D9	999

```

0001      SUBROUTINE MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
0002      V=V*1.E05
0003      T1=0.009*SQRT(V)*RHOP*D**2.0
0004      T1=T1/(S*RHO**1.5)
0005      T2=T1
0006      RETURN
0007      END

```

## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	69	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	69	

## ENTRY POINTS

Address	Type	Name
0-00000000		MADDEN

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	AP-00000014@	R*4	RHO	AP-0000000C@	R*4	RHOP
AP-00000018@	R*4	T1	AP-0000001C@	R*4	T2	AP-00000004@	R*4	V
AP-00000024@	R*4	WTCMC						

## FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT



```

0001      SUBROUTINE WILKINSON(V,D,RHOP,RH01,RH02,S,XL2,
0002      &      T1,T2,WT,WTCMC)
0003      T1=0.604*D**2.*RHOP/S
0004      T1=T1*SQRT(V/(XL2*RH01*RH02))
0005      RATIO=D*RHOP/(T1*RH01)
0006      IF(RATIO.GT.1.0)T2=T1
0007      IF(RATIO.LE.1.0)T2=T1/RATIO
0008      RETURN
0009      END

```

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## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	87	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	87	

## ENTRY POINTS

Address	Type	Name
0-00000000		WILKINSON

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	RATIO	AP-00000010@	R*4	RH01
AP-0000000C@	R*4	RHOP	AP-00000018@	R*4	S	AP-00000020@	R*4	T1
AP-00000004@	R*4	V	AP-00000028@	R*4	WT	AP-0000002C@	R*4	WTCMC

## FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

```

0001 ***** MODIFIED BURCH *****
0002 SUBROUTINE BURCH(V,D,RH01,S,THETA,
0003 & XN,E1,T1,T2,WT,WTCMC)
0004 VB=V*3280.
0005 DB=D/2.54
0006 CM=SQRT(E1/RH01)
0007 CM=CM/30.48
0008 SB=S/2.54
0009 IF(THETA.LE.0.001)GO TO 425
0010 CHI=TAN(THETA)-0.5
0011 F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0012 F2=F2+(1.7-12.*T1B/D)*CHI
0013 F3=0.32*(T1B/D)**0.83
0014 F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0015 T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
0016 T2F=T2F*(D/S)**0.71
0017 T2N=F3*(CM/V)**1.33*D/XN
0018 IF(T2N.GE.T2F)T2B=T2N
0019 IF(T2N.LT.T2F)T2B=T2F
0020 T2B=T2B*2.54
0021 IF(T2B.GT.T2)NREGION=3
0022 IF(T2B.GT.T2)T2=T2B
0023 GO TO 499
0024 425 CONTINUE
0025 NITSB=0
0026 XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0027 VDELTA=0.0
0028 DELTA3=0.52
0029 1099 DELTA2=2.33*(1.-1.57*DELTA3)
0030 DELTA1=1.33*(2.*DELTA3-1.)
0031 VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
0032 VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
0033 IF(VDELTA1.LT.VDELTA)THEN
0034 DELTA1=1.33*(2.*DELTA3-1.04)
0035 T1=DELTA1*VDELTA
0036 T2=VDELTA-T1
0037 GO TO 499
0038 ENDIF
0039 VDELTA=VDELTA1
0040 DELTA3=DELTA3+0.02
0041 IF(DELTA3.GT.0.63)THEN
0042 T1=DELTA1*VDELTA
0043 T2=VDELTA-T1
0044 GO TO 499
0045 ENDIF
0046 GO TO 1099
0047 499 CONTINUE
0048 T1=T1*2.54
0049 T2=T2*2.54
0050 RETURN
0051 END

```

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## IMPACT5VM

IMPACT5VM is a spacecraft protective systems design optimization code similar to IMPACT5V. IMPACT5VM differs from IMPACT5V in that the optimal design is weighted according to the chosen meteoroid velocity probability distribution. IMPACT5VM employs the Geometric Programming optimization technique in evaluating a number of nonlinear piecewise continuous, functional impact predictors. These include the Nysmith, Boeing, Madden, Wilkinson, and Burch predictors. Inputs vary depending on the predictor used, however, typical inputs include the meteoroid velocity distribution file, projectile characteristics (as determined from METEOR1 or DEBRIS1), design material properties, and general design configuration. In particular, IMPACT5VM is an optimization code for a single bumper, single wall configuration. Outputs include the optimal design thicknesses (bumper and wall) and the minimum design weight. The velocity distribution file for meteoroids, (METVEL.IN), follows. The file being used must be assigned to FOR012 before running IMPACT5VM. Sample input (IMPACT5VM.IN), output (IMPACT5VM.OUT), and program listing (IMPACT5VM.LIS) follow the velocity distribution file.

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23	.10
24	.10
25	.06
26	.06
27	.06
28	.05
29	.05
30	.05
31	.025
32	.025
33	.025
34	.015
35	.015
36	.015
37	.012
38	.012
39	.012
40	.011
41	.011
42	.011
43	.009
44	.009
45	.009
46	.0075
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5	!NUMBER OF CASES
1	!NYSMITH PREDICTOR
0.84	!PROJ. DIAMETER IN CM
10.	!BUMPER/WALL SEPARATION IN CM
2	!BOEING PREDICTOR
0.84	!PROJ. DIA. IN CM
2.81	!PROJ. DENSITY IN GM/CUBIC CM
2.81	!BUMPER DENSITY IN GM/CUBIC CM
2.81	!WALL DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
0.401	!WALL MATERIAL CONSTANT
7344000.	!BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000.	!WALL YIELD STRENGTH IN LB/SQUARE FOOT
0.	!IMPACT ANGLE FROM NORMAL
0.85	!NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11	!YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
3	!MADDEN PREDICTOR
0.84	!PROJ. DIA. IN CM
2.81	!PROJ. DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
2.81	!BUMPER/WALL DENSITY IN GM/CUBIC CM
4	!WILKINSON PREDICTOR
0.84	!PROJ. DIA. IN CM
2.81	!PROJ. DENSITY IN GM/CUBIC CM
2.81	!BUMPER DENSITY IN GM/CUBIC CM
2.81	!WALL DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
0.401	!WALL MATERIAL CONSTANT
5	!BURCH PREDICTOR
0.84	!PROJ. DIA. IN CM
2.81	!BUMPER DENSITY IN GM/CUBIC CM
10.	!BUMPER/WALL SEPARATION IN CM
0.	!IMPACT ANGLE FROM NORMAL
0.85	!NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11	!YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC

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NYSMITH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000  
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.2964782 CM  
WALL THICKNESS = 0.5514496 CM  
MIN. WEIGHT = 0.8479279 CM  
CMC MIN. WEIGHT = 4373.689 KG

BOEING

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000  
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER DENSITY IN GM/CUBIC CM = 2.810000  
WALL DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000  
WALL MATERIAL CONSTANT = 0.4010000  
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.  
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.  
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00  
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000  
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 0.3065161 CM  
WALL THICKNESS = 0.3286171 CM  
MIN. WEIGHT = 0.6351332 CM  
CMC MIN. WEIGHT = 3294.346 KG

MADDEN

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000  
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.5543199 CM  
WALL THICKNESS = 0.5543199 CM  
MIN. WEIGHT = 1.108640 CM  
CMC MIN. WEIGHT = 5761.344 KG

WILKINSON

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000  
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER DENSITY IN GM/CUBIC CM = 2.810000  
WALL DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000  
WALL MATERIAL CONSTANT = 0.4010000

OUTPUT

BUMPER THICKNESS = 0.3114124 CM  
WALL THICKNESS = 0.3114124 CM  
MIN. WEIGHT = 0.6228247 CM  
CMC MIN. WEIGHT = 3233.087 KG

MODIFIED BURCH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000  
BUMPER DENSITY IN GM/CUBIC CM = 2.810000  
BUMPER/WALL SEPARATION IN CM = 10.00000  
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00  
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000  
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 4.5066189E-02CM  
WALL THICKNESS = 9.7935580E-02CM  
MIN. WEIGHT = 0.1430018 CM  
CMC MIN. WEIGHT = 735.0610 KG

```

0001      DIMENSION XPV(100)
0002      OPEN(UNIT=12,TYPE='OLD',ACCESS='SEQUENTIAL')
0003      OPEN(UNIT=10,TYPE='OLD',NAME='IMPACT5VM.IN',ACCESS='SEQUENTIAL')
0004      OPEN(UNIT=11,TYPE='NEW',NAME='IMPACT5VM.OUT',ACCESS='SEQUENTIAL')
0005      DO 24 I=1,64
0006          READ(12,*)IV,XPV(IV)
0007      24  CONTINUE
0008      READ(10,*)NRUNS
0009      DO 10 I=1,NRUNS
0010          READ(10,*)NCODE
0011          IF(NCODE.EQ.1)GO TO 25
0012          IF(NCODE.EQ.2)GO TO 35
0013          IF(NCODE.EQ.3)GO TO 45
0014          IF(NCODE.EQ.4)GO TO 55
0015          IF(NCODE.EQ.5)GO TO 65
0016      25  READ(10,*)D
0017          READ(10,*)H
0018          WRITE(11,*)'      NYSMITH'
0019          WRITE(11,*)
0020          WRITE(11,*)'      INPUT'
0021          WRITE(11,*)
0022          WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0023          WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',H
0024          WRITE(11,*)
0025          T1T=0.0
0026          T2T=0.0
0027          DO 26 J=1,64
0028              K=J+8
0029              V=FLOAT(K)
0030              CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
0031              T1T=T1T+T1*XPV(K)
0032              T2T=T2T+T2*XPV(K)
0033      26  CONTINUE
0034          T1=T1T/3.1335
0035          T2=T2T/3.1335
0036          WT=T1+T2
0037          WTCMC=T1**2.+2.*T1*(211.+T2+H)+T2**2.+422.*T2
0038          WTCMC=12.*WTCMC
0039          WRITE(11,*)'      OUTPUT'
0040          WRITE(11,*)
0041          WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0042          WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0043          WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0044          WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0045          WRITE(11,*)
0046          WRITE(11,*)
0047          WRITE(11,*)
0048          GO TO 10
0049      35  READ(10,*)D
0050          READ(10,*)RHOP
0051          READ(10,*)RH01
0052          READ(10,*)RH02
0053          READ(10,*)S
0054          READ(10,*)XL2
0055          READ(10,*)SY1
0056          READ(10,*)SY2
0057          READ(10,*)THETA

```

```

0058      READ(10,*)XN
0059      READ(10,*)E1
0060      WRITE(11,*)'      BOEING'
0061      WRITE(11,*)
0062      WRITE(11,*)'      INPUT'
0063      WRITE(11,*)
0064      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0065      WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0066      WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0067      WRITE(11,*)'      WALL DENSITY IN GM/CUBIC CM = ',RH02
0068      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
0069      WRITE(11,*)'      WALL MATERIAL CONSTANT = ',XL2
0070      WRITE(11,*)'      BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
0071      WRITE(11,*)'      WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
0072      WRITE(11,*)'      IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
0073      WRITE(11,*)'      NUMBER OF PLATES TO PENETRATE AFTER FIRST',
0074      &          '      BUMPER = ',XN
0075      WRITE(11,*)'      BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
0076      &          '      SEC = ',E1
0077      WRITE(11,*)
0078      T1T=0.0
0079      T2T=0.0
0080      DO 36 J=1,64
0081      K=J+8
0082      V=FLOAT(K)
0083      CALL BOEING(V,D,RHOP,RH01,RH02,S,XL2,SY1,SY2,THETA,
0084      &          XN,E1,T1,T2,WT,WTCMC)
0085      T1T=T1T+XPV(K)*T1
0086      T2T=T2T+XPV(K)*T2
0087 36      CONTINUE
0088      T1=T1T/3.1335
0089      T2=T2T/3.1335
0090      WT=T1+T2
0091      R12=211.
0092      R22=211.+T2
0093      R11=211.+T2+S
0094      R21=211.+T1+T2+S
0095      VB=4.27*(R21**2.-R11**2.)
0096      VW=4.27*(R22**2.-R12**2.)
0097      WTCMC=RH01*VB+RH02*VW
0098      WRITE(11,*)'      OUTPUT'
0099      WRITE(11,*)
0100      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0101      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0102      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0103      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0104      WRITE(11,*)
0105      WRITE(11,*)
0106      WRITE(11,*)
0107      GO TO 10
0108 45      READ(10,*)D
0109      READ(10,*)RHOP
0110      READ(10,*)S
0111      READ(10,*)RHO
0112      WRITE(11,*)'      MADDEN'
0113      WRITE(11,*)
0114      WRITE(11,*)'      INPUT'

```

```

0115      WRITE(11,*)
0116      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0117      WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0118      WRITE(11,*)'      BUMPER/WALL DENSITY IN GM/CUBIC CM = ',RHO
0119      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S

```

```

0120      WRITE(11,*)
0121      T1T=0.0
0122      T2T=0.0
0123      DO 46 J=1,64
0124      K=J+8

```

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```

0125      V=FLOAT(K)
0126      CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
0127      T1T=T1T+T1*XPV(K)
0128      T2T=T2T+T2*XPV(K)

```

46

```

0129      CONTINUE
0130      T1=T1T/3.1335
0131      T2=T2T/3.1335
0132      WT=T1+T2
0133      R12=211.
0134      R22=211.+T2
0135      R11=211.+T2+S
0136      R21=211.+T1+T2+S
0137      VB=4.27*(R21**2.-R11**2.)
0138      VW=4.27*(R22**2.-R12**2.)
0139      WTCMC=RHO*(VB+VW)

```

OUTPUT'

```

0140      WRITE(11,*)'
0141      WRITE(11,*)
0142      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0143      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0144      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0145      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0146      WRITE(11,*)
0147      WRITE(11,*)
0148      WRITE(11,*)

```

55

```

0149      GO TO 10
0150      READ(10,*)D
0151      READ(10,*)RHOP
0152      READ(10,*)RHO1
0153      READ(10,*)RHO2
0154      READ(10,*)S
0155      READ(10,*)XL2

```

WILKINSON'

```

0156      WRITE(11,*)'
0157      WRITE(11,*)
0158      WRITE(11,*)'
0159      WRITE(11,*)

```

INPUT'

```

0160      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0161      WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0162      WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
0163      WRITE(11,*)'      WALL DENSITY IN GM/CUBIC CM = ',RHO2
0164      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
0165      WRITE(11,*)'      WALL MATERIAL CONSTANT = ',XL2

```

```

0166      WRITE(11,*)
0167      T1T=0.0
0168      T2T=0.0
0169      DO 56 J=1,64
0170      K=J+8
0171      V=FLOAT(K)

```

```

)172      CALL WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,
)173      &      T1,T2,WT,WTCMC)
)174      T1T=T1T+T1*XPV(K)
)175      T2T=T2T+T2*XPV(K)
)176      56      CONTINUE
)177      T1=T1T/3.1335
)178      T2=T2T/3.1335
)179      WT=T1+T2
)180      R12=211.
)181      R22=211.+T2
)182      R11=211.+T2+S
)183      R21=211.+T1+T2+S
)184      VB=4.27*(R21**2.-R11**2.)
)185      VW=4.27*(R22**2.-R12**2.)
)186      WTCMC=RHO1*VB+RHO2*VW
)187      WRITE(11,*)'      OUTPUT'
)188      WRITE(11,*)
)189      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
)190      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
)191      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
)192      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
)193      WRITE(11,*)
)194      WRITE(11,*)
)195      WRITE(11,*)
)196      GO TO 10
)197      65      READ(10,*)D
)198      READ(10,*)RH01
)199      READ(10,*)S
)200      READ(10,*)THETA
)201      READ(10,*)XN
)202      READ(10,*)E1
)203      ***** MODIFIED BURCH *****
)204      WRITE(11,*)'      MODIFIED BURCH'
)205      WRITE(11,*)
)206      WRITE(11,*)'      INPUT'
)207      WRITE(11,*)
)208      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
)209      WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RH01
)210      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
)211      WRITE(11,*)'      IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
)212      WRITE(11,*)'      NUMBER OF PLATES TO PENETRATE AFTER FIRST',
)213      &      ' BUMPER = ',XN
)214      WRITE(11,*)'      BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
)215      &      ' SEC = ',E1
)216      WRITE(11,*)
)217      T1T=0.0
)218      T2T=0.0
)219      DO 66 J=1,64
)220      K=J+8
)221      V=FLOAT(K)
)222      CALL BURCH(V,D,RHO1,S,THETA,
)223      &      XN,E1,T1,T2,WT,WTCMC)
)224      T1T=T1T+T1*XPV(K)
)225      T2T=T2T+T2*XPV(K)
)226      66      CONTINUE
)227      T1=T1T/3.1335
)228      T2=T2T/3.1335

```



```

0229      WT=T1+T2
0230      R12=211.
0231      R22=211.+T2
0232      R11=211.+T2+S
0233      R21=211.+T1+T2+S
0234      VB=4.27*(R21**2.-R11**2.)
0235      VW=4.27*(R22**2.-R12**2.)
0236      WTCMC=RHO1*VB+2.81*VW
0237      WRITE(11,*)'      OUTPUT'
0238      WRITE(11,*)
0239      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0240      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0241      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0242      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0243      WRITE(11,*)
0244      WRITE(11,*)
0245      WRITE(11,*)
0246      GO TO 10
0247  10    CONTINUE
0248      STOP
0249      END

```

## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	4826	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	743	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	1028	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	6597	

## ENTRY POINTS

Address	Type	Name
0-00000000		IMPACT5VM\$MAIN

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
2-0000019C	R*4	D	2-000001DC	R*4	E1	2-000001A0	R*4	H
2-00000190	I*4	IV	**	I*4	J	**	I*4	K
2-00000194	I*4	NRUNS	**	R*4	R11	**	R*4	R12
**	R*4	R22	2-000001E0	R*4	RHO	2-000001BC	R*4	RHO1
2-000001B8	R*4	RHOP	2-000001C4	R*4	S	2-000001CC	R*4	SY1
2-000001A8	R*4	T1	**	R*4	T1T	2-000001AC	R*4	T2
2-000001D4	R*4	THETA	2-000001A4	R*4	V	**	R*4	VB
2-000001B0	R*4	WT	2-000001B4	R*4	WTCMC	2-000001C8	R*4	XL2

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SAI\_USRDIS

```

)001      SUBROUTINE NYSMITH(V,D,H,T1,T2,WT,WTCMC)
)002      DMAX=0.24*H*V**-0.2
)003      IF(D.GT.DMAX)THEN
)004          WRITE(11,*)'      NO SOLUTION--PROJ. DIA. TOO LARGE FOR NYSMITH'
)005          GO TO 16
)006      ENDIF
)007      T1=1.93*V**0.18*D**1.91/H**0.91
)008      T2=1.86*T1
)009      16      CONTINUE
)010      RETURN
)011      END

```

## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	150	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	49	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	8	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	207	

## ENTRY POINTS

Address	Type	Name
0-00000000		NYSMITH

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	DMAX	AP-0000000C@	R*4	H
AP-00000014@	R*4	T2	AP-00000004@	R*4	V	AP-00000018@	R*4	WT

## LABELS

Address	Label
0-00000095	16

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SAI\_USRDISK

```

0001      SUBROUTINE BOEING(V,D,RHOP,RH01,RH02,S,XL2,SY1,SY2,THETA,
0002      &      XN,E1,T1,T2,WT,WTCMC)
0003      ***** PEN4 *****
0004      T1=0.16
0005      V=V*3280.
0006      D=D/30.48
0007      RP=D/2.0
0008      RHOP=RHOP*1.94
0009      RH01=RH01*1.94
0010      RH02=RH02*1.94
0011      NITSP=0
0012      NITSP=NITSP+1
0013      NP1=0
0014      T1P=T1/30.48
0015      T2P=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P)
0016      WT=T1P+T2P
0017      IF(NITSP.EQ.1)THEN
0018          T1P1=1.1*T1P
0019          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0020          WT1=T1P1+T2P1
0021      ENDIF
0022      IF(WT1.GT.WT)THEN
0023          T1P1=0.82*T1P1
0024          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0025          WT1=T1P1+T2P1
590      IF(WT1.GT.WT)THEN
0027          GO TO 601
0028      ELSE
0029          T1P=T1P1
0030          T2P=T2P1
0031          WT=WT1
0032          NP1=NP1+1
0033          IF(NP1.EQ.100)THEN
0034              WRITE(11,*)' NO CONVERGENCE IN PEN4'
0035              GO TO 557
0036          ENDIF
0037          T1P1=0.9*T1P1
0038          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0039          WT1=T1P1+T2P1
0040          GO TO 590
0041      ENDIF
0042      ELSE
579      T1P=T1P1
0043          T2P=T2P1
0044          WT=WT1
0045          T1P1=1.1*T1P1
0046          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P1)
0047          WT1=T1P1+T2P1
0048          IF(WT1.GT.WT)THEN
0049              GO TO 601
0050          ELSE
0051              NP1=NP1+1
0052              IF(NP1.EQ.100)THEN
0053                  WRITE(11,*)' NO CONVERGENCE IN PEN4'
0054                  GO TO 557
0055              ENDIF
0056              GO TO 579
0057

```

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```
0058         ENDIF
0059         ENDIF
0060     601     CONTINUE
0061         D=30.48*D
0062         RHOP=RHOP/1.94
0063         RH01=RH01/1.94
0064         RH02=RH02/1.94
0065         T1P=30.48*T1P
0066         T2P=30.48*T2P
0067         IF(T1P/D.LE.0.4)VF=4100
0068         IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
0069         VF=VF+4000.
0070         IF(V.LE.VF)THEN
0071             WRITE(11,*)'    INSIDE OF PEN4 LIMITS'
0072             T1=T1P
0073             T2=T2P
0074             GO TO 1102
0075         ENDIF
0076     557     CONTINUE
0077     ***** WILKINSON *****
0078         V=V/3280.
0079         T1=0.604*D**2.*RHOP/S
0080         T1=T1*SQRT(V/(XL2*RH01*RH02))
0081         RATIO=D*RHOP/(T1*RH01)
0082         IF(RATIO.GT.1.0)T2=T1
0083         IF(RATIO.LE.1.0)T2=T1/RATIO
0084     ***** MODIFIED BURCH *****
0085         VB=V*3280.
0086         DB=D/2.54
0087         CM=SQRT(E1/RH01)
0088         CM=CM/30.48
0089         SB=S/2.54
0090         IF(THETA.LE.0.001)GO TO 125
0091         CHI=TAN(THETA)-0.5
0092         F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0093         F2=F2+(1.7-12.*T1B/D)*CHI
0094         F3=0.32*(T1B/D)**0.83
0095         F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0096         T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
0097         T2F=T2F*(D/S)**0.71
0098         T2N=F3*(CM/V)**1.33*D/XN
0099         IF(T2N.GE.T2F)T2B=T2N
0100         IF(T2N.LT.T2F)T2B=T2F
0101         T2B=T2B*2.54
0102         IF(T2B.GT.T2)NREGION=3
0103         IF(T2B.GT.T2)T2=T2B
0104         GO TO 155
0105     125     CONTINUE
0106         T1B1=T1/2.54
0107         NITSB=0
0108         XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0109         VDELTA=0.0
0110         DELTA3=0.52
0111     1099     DELTA2=2.33*(1.-1.57*DELTA3)
0112         DELTA1=1.33*(2.*DELTA3-1.)
0113         VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
0114         VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
```

BOEING

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SAI\_USRDISK

```

0115      IF(VDELTA1.LT.VDELTA)THEN
0116          DELTA1=1.33*(2.*DELTA3-1.04)
0117          T1B=DELTA1*VDELTA
0118          T2B=VDELTA-T1B
0119          GO TO 499
0120      ENDIF
0121      VDELTA=VDELTA1
0122      DELTA3=DELTA3+0.02
0123      IF(DELTA3.GT.0.63)THEN
0124          T1B=DELTA1*VDELTA
0125          T2B=VDELTA-T1B
0126          GO TO 499
0127      ENDIF
0128      GO TO 1099
0129      499      CONTINUE
0130      ***** COMPARISON OF MODIFIED BURCH AND WILKINSON *****
0131      199      CONTINUE
0132          T10W=T1/2.54
0133          F10W=1.58*(DB/T10W)**0.57+2.80*(T10W/DB)**0.57
0134          T2BT10W=(F10W/XN)**1.71*(CM/VB)**2.29*DB**1.71
0135          T2BT10W=T2BT10W/SB**0.71
0136          T2BT10W=T2BT10W*2.54
0137          RATIOB=(DB*RHOP)/(RH01*T1B)
0138          T2WT10B=0.364*D**3.*RHOP*V/(XL2*RH02*S**2.)
0139          IF(RATIOB.GT.1.0)T2WT10B=T2WT10B*RATIOB
0140          IF(T2BT10W.GT.T2)T2=T2BT10W
0141          T2B=T2B*2.54
0142          IF(T2WT10B.GT.T2B)T2B=T2WT10B
0143          T1B=T1B*2.54
0144          IF(T1B+T2B.LT.T1+T2)THEN
0145              T1=T1B
0146              T2=T2B
0147          ENDIF
0148      155      CONTINUE
0149      1102      IF(T2.LE.0.01)THEN
0150          SIGMA=SY2/144.
0151          T2=3099.1/SIGMA
0152      ENDIF
0153      156      RETURN
0154      END
```

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VAX FORT  
SAI\_USRDIS

```
0001      FUNCTION FT2B(DB,T1B,XN,CM,VB,SB)
0002      F1=2.42*(DB/T1B)**0.33+4.26*(T1B/DB)**0.33
0003      F1=F1-4.18
0004      FT2B=(F1/XN)**1.71*(CM/VB)**2.29*DB**1.71/SB**0.71
0005      RETURN
0006      END
```

#### PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	163	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	167	

#### ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2B

#### VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000010@	R*4	CM	AP-00000004@	R*4	DB	**	R*4	F1
AP-00000008@	R*4	T1B	AP-00000014@	R*4	VB	AP-0000000C@	R*4	XN

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SAI\_USRDISK

```

0001      FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P)
0002      A=1.33*RHOP*(V*RP)**2.
0003      B=8.0*SY1*EXP(-3.125E-04*V)/COS(THETA)
0004      C=1.33*RHOP*RP**2.0
0005      D1=RP*RH01/COS(THETA)
0006      XK1=1.67*(RHOP/(2.*SY2))**0.31
0007      XK1=XK1*(0.281*D*RHOP/RH02)**0.33
0008      XK1=XK1*COS(THETA)
0009      C1P1=(A-B*T1P)/(C+D1*T1P)
0010      IF(C1P1.LE.0.001)THEN
0011          FT2P=0.0
0012          GO TO 999
0013      ENDIF
0014      FT2P=XK1*C1P1**0.31
0015      999      RETURN
0016      END

```

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## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	222	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	226	

## ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2P

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
**	R*4	A	**	R*4	B	**	R*4	C
AP-00000020@	R*4	D	**	R*4	D1	AP-00000018@	R*4	RH01
AP-00000004@	R*4	RHOP	AP-0000000C@	R*4	RP	AP-00000010@	R*4	SY1
AP-00000028@	R*4	T1P	AP-00000014@	R*4	THETA	AP-00000008@	R*4	V

## LABELS

Address	Label
0-000000D9	999

```

J001      SUBROUTINE MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
J002      V=V*1.E05
J003      T1=0.009*SQRT(V)*RHOP*D**2.0
J004      T1=T1/(S*RHO**1.5)
J005      T2=T1
J006      RETURN
J007      END

```

## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	69	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	69	

## ENTRY POINTS

Address	Type	Name
0-00000000		MADDEN

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	AP-00000014@	R*4	RHO	AP-0000000C@	R*4	RHOP
AP-00000018@	R*4	T1	AP-0000001C@	R*4	T2	AP-00000004@	R*4	V
AP-00000024@	R*4	WTCMC						

## FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

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SAI\_USRDISK

```
0001      SUBROUTINE WILKINSON(V,D,RHOP,RH01,RH02,S,XL2,  
0002      &          T1,T2,WT,WTCMC)  
0003      T1=0.604*D**2.*RHOP/S  
0004      T1=T1*SQRT(V/(XL2*RH01*RH02))  
0005      RATIO=D*RHOP/(T1*RH01)  
0006      IF(RATIO.GT.1.0)T2=T1  
0007      IF(RATIO.LE.1.0)T2=T1/RATIO  
0008      RETURN  
0009      END
```

## PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	87	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	87	

## ENTRY POINTS

Address	Type	Name
0-00000000		WILKINSON

## VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	RATIO	AP-00000010@	R*4	RH01
AP-0000000C@	R*4	RHOP	AP-00000018@	R*4	S	AP-00000020@	R*4	T1
AP-00000004@	R*4	V	AP-00000028@	R*4	WT	AP-0000002C@	R*4	WTCMC

## FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

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SAI\_USRD

```
***** MODIFIED BURCH *****
0001 SUBROUTINE BURCH(V,D,RH01,S,THETA,
0002 & XN,E1,T1,T2,WT,WTCMC)
0003
0004 VB=V*3280.
0005 DB=D/2.54
0006 CM=SQRT(E1/RH01)
0007 CM=CM/30.48
0008 SB=S/2.54
0009 IF(THETA.LE.0.001)GO TO 425
0010 CHI=TAN(THETA)-0.5
0011 F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0012 F2=F2+(1.7-12.*T1B/D)*CHI
0013 F3=0.32*(T1B/D)**0.83
0014 F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0015 T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
0016 T2F=T2F*(D/S)**0.71
0017 T2N=F3*(CM/V)**1.33*D/XN
0018 IF(T2N.GE.T2F)T2B=T2N
0019 IF(T2N.LT.T2F)T2B=T2F
0020 T2B=T2B*2.54
0021 IF(T2B.GT.T2)NREGION=3
0022 IF(T2B.GT.T2)T2=T2B
0023 GO TO 499
0024 425 CONTINUE
0025 NITSB=0
0026 XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0027 VDELTA=0.0
0028 DELTA3=0.52
0029 1099 DELTA2=2.33*(1.-1.57*DELTA3)
0030 DELTA1=1.33*(2.*DELTA3-1.)
0031 VDELTA1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
0032 VDELTA1=VDELTA1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
0033 IF(VDELTA1.LT.VDELTA)THEN
0034 DELTA1=1.33*(2.*DELTA3-1.04)
0035 T1=DELTA1*VDELTA
0036 T2=VDELTA-T1
0037 GO TO 499
0038 ENDIF
0039 VDELTA=VDELTA1
0040 DELTA3=DELTA3+0.02
0041 IF(DELTA3.GT.0.63)THEN
0042 T1=DELTA1*VDELTA
0043 T2=VDELTA-T1
0044 GO TO 499
0045 ENDIF
0046 GO TO 1099
0047 499 CONTINUE
0048 T1=T1*2.54
0049 T2=T2*2.54
0050 RETURN
0051 END
```